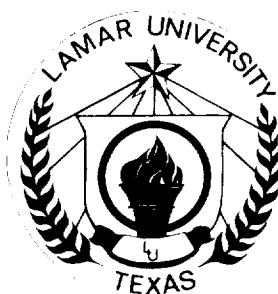


Lamar University

BEAUMONT, TEXAS

TECHNICAL REPORT



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SOURCES FOR SPACECRAFT APPLICATIONS
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**Evaluation of Actuator Energy Storage and
Power Sources for Spacecraft Applications**

FINAL REPORT

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**Lamar University
College of Engineering
Beaumont, Texas**

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Introduction

The objective of this evaluation is to determine an optimum energy storage/power source combination for electrical actuation systems for existing (Solid Rocket Boster (SRB), Shuttle) and future (Advanced Launch System (ALS), Shuttle Derivative) vehicles. Characteristic of these applications is the requirement for high power pulses (50 - 200 kW) for short times (milliseconds to seconds), coupled with longer-term base or "housekeeping" requirements (5 - 16 kW). Specific study parameters (e.g., weight, volume, etc.) as stated in the proposal and specified in the Statement of Work [1]* are included in Table 1.

Approach

The overall approach to this analysis is presented in Table 2, where it should be noted that detailed evaluation of actuator devices proper is not intended, but the characteristics of these devices are included insofar as they are necessary to determine the power requirements of the electrical power or energy storage source. A five-part work plan for this effort is shown in Table 3, together with a schedule of activities (Table 4). At the request of NASA, related work beginning in the May-June 1992 time frame under another grant (NAG 9-626) necessitated an extension of the original schedule of this activity to May 1993. A mid-term briefing and report were submitted in February 1992 [2], and this report documents the results of that effort plus work done from that time to this date. Essentially, work done through February 1992 was concentrated on launch vehicle applications, with the remainder of the time spent on Shuttle and advanced applications. Team assignments for the six-person team of faculty and research assistants are listed in Table 5.

Although the study was focused for the first 6 months on battery systems for Solid Rocket Booster (SRB) and Advanced Launch System (ALS) applications, work on the overall study objectives continued throughout the past 18 months on the full spectrum of applications and energy storage/power source systems. To insure use of the latest available technology, much of the results obtained were derived through telecons and information exchange with JSC-supplied government and industry contacts, as well as other contacts developed through the course of the study by the Lamar Team. A list of organizations and individuals with whom the Team has been in contact is supplied in Table 6.

*Numbers in brackets refer to similarly numbered references at the end of this report.

Search of the Literature

An electronic literature search was conducted both at Lamar University and at the JSC Technical Library. This initial effort resulted in some 108 apparently relevant documents. This list was subsequently reduced to 31 documents of interest. As the study progressed, other relevant documents were located and added to the list. Additional publications and other unpublished information (briefings, analyses, and telecon notes) provided by Mr. Bob Bragg and Mrs. Elizabeth Kluksdal of the Power Branch at JSC were very helpful. Also, textbooks provided by JSC personnel, as well as some obtained during the course of the study, proved to be of value in the investigation. Perhaps the most important information, however, has been provided by the many technical contacts provided by JSC personnel. Since the state of technology of the various power source candidates is changing rapidly, these industry and government contacts have proved to be most valuable in assuring that the study is based not solely on textbook information. At the same time, though these industry and government contacts tend to assist greatly in gathering relevant information, each one is partial to his particular technology, and this has required that judgment factors be applied in the evaluation process. Although new sources of information are still being discovered, it is felt that the references used to date have been adequate. In addition to the specific references provided at the end of this report, a list of additional bibliographical sources is also supplied for completeness.

Vehicle Applications Identification

Identification of spacecraft/vehicle applications and specific system requirements was completed early in the study for the various types of launch vehicles examined, and this activity was later resumed for Shuttle-type applications (see overall study schedule, Table 4). Assistance was provided by knowledgeable personnel from JSC, MSFC, and the Rockwell International Corporation. Table 7 includes applications identified for SRB and other launch-type vehicles, and for Shuttle-type vehicles. At NASA's request, near-term study objectives were concentrated on the SRB and ALS applications. Effort was expended on Shuttle-type vehicles later in the study.

Launch Vehicle Case -- Evaluation and Results

Power requirements were derived for the SRB and ALS applications. Because heavy-lift vehicles of the future could not be well defined at this time, no specific power requirements could be obtained; however, it appears reasonable to assume that these requirements may be similar to those of a typical ALS or SRB vehicle; hence, further effort was not expended in defining power requirements for heavy-lift vehicles. Additionally, because of a special interest by NASA Headquarters in batteries as a launch vehicle power source, the power source investigation for launch vehicles was concentrated on batteries and high-energy-rate capacitors. This was natural, since the short times of operation for the SRB (approximately 2 minutes) and the ALS (approximately 10 minutes) would not justify certain other power sources, e.g., a dedicated fuel cell, with its requirement for external reactants, cooling, etc. In future studies it may be desirable to investigate the applicability of

flywheels or other systems in more detail, but this was not done here due to the low state of technology development of these systems in this size range, although certain prototypes have been built [3].

Figure 1 shows the SRB power requirement at the actuator bus. However, to be of use in the study it was necessary that this power requirement be calculated at the battery terminal(s). To do this, power conditioner and associated line losses had to be assumed. Neglecting for the time being the differences in electronic equipment between an ac or dc actuator motor system, from an energy/power standpoint, an assumption of 90% efficiency was made for the power conditioning/conversion(dc)/inversion(ac) system, coupled with a 2% line loss (see Figure 2). This results in an SRB power requirement at the battery terminals as shown in Figure 3. For the ALS, power requirements at the power source (battery terminals) are given in Figure 4. The principal difference between these two applications is in the duration and frequency of the power required, and the fact that the SRB peak power level is approximately 40% higher than that of the ALS. The ALS power pulses are farther apart timewise (10 sec vs 4.25 sec for the SRB), and they are one-third the duration of the SRB pulses, making the ALS application less stringent overall from a battery discharge rate standpoint. Figure 5 defines power and energy requirements in detail for both the SRB and ALS applications. From this figure it is evident that the most difficult requirement to meet is that of the SRB, and for this reason this part of the investigation was focused on the challenge of the SRB for ELA application.

This focus on battery systems for launch vehicle applications has resulted in the initial investigation of 14 battery types or technologies over the course of the study, plus one hybrid system, and the thermal battery technology (Table 8). Results of the investigation are summarized on an evaluation sheet for each battery technology (Tables 9 through 22). In addition to batteries, four types of high-rate capacitors were also investigated, which are described later in this report.

For the launch vehicle applications described above (SRB and ALS), it soon became apparent that these very high-rate, relatively low-energy requirements would require battery discharge rates in the 90 - 100 "C" range for many existing batteries, unless these batteries were re-sized upward considerably to absorb the punishing high-rate pulses to which they would be subjected. Some of the battery technologies in the original list were chosen based on current research being conducted for the electric automobile. Other candidates were technologies which had previously been used in the NASA space program or other aerospace programs, or ones which had undergone significant technology improvements in recent years. Closer examination of the various battery technologies against launch vehicle requirements suggested three things:

- (a) battery selection, in the overall analysis, is driven mostly by (1) operational requirements and intended use, e.g., pre-launch checkout, remote activation, whether or not the vehicle is reusable or disposable, etc.; and (2) capability of a particular battery for high-rate discharge performance.

- (b) silver-zinc batteries with high-rate capability in the same range needed for this application (90 "C" and above) were used in the Apollo program, and although their basic technology has not changed much over the years, this technology appears attractive today for this application, particularly the primary, or single-use, silver-zinc battery.
- (c) other battery technologies, such as advanced nickel-cadmium, bipolar lead-acid, and common-pressure-vessel nickel-hydrogen, have undergone significant technological advances in recent years, making them attractive for this application.

Consequently, the list of feasible candidates was reduced for the launch vehicle application to the following:

- Automatically Activated Ag-Zn Primary
- Bipolar Lead-Acid (primary)
- Manually Activated Ag-Zn (secondary)
- CPV Ni-H₂ (non-bipolar) (secondary)
- Advanced Ni-Cd (secondary)
 - Fiber-Nickel-Cadmium
- Metallic Hydride

For these candidate technologies, further indepth studies were performed based on up-to-date vendor information, and preliminary comparative sizing of these batteries for the derived SRB power profile described above was performed. A summary of these results is shown in condensed form in Tables 23 through 28. The results of the comparative sizing study are shown in Table 29, and Table 30 repeats these results in more condensed form, plus adds relative merit ratings for technology readiness and an operations impact (complexity, safety). Although these merit ratings are highly subjective and were the subject of much debate among manufacturers, government personnel, and the grant investigators, they are included here as the best estimate of the investigators, and only because this is a requirement of the Statement of Work. The reader is cautioned against using these merit ratings in a quantitative sense.

The use of capacitors in conjunction with batteries was evaluated for launch vehicle applications. Four types of high-energy, high-rate capacitors were investigated:

- Electrolytic Pulse-Forming Network (PFN)
- High-Voltage (HV) Capacitors
- Chemical Double-Layer (CDL)
- Isuzu "Ultracapacitor" (UC)

Results of the capacitor investigation indicate that:

- (a) While the use of high-energy, high-rate capacitors in conjunction with batteries for launch-vehicle ELA application would relieve the high-rate stress on any battery system, primary or secondary, further reducing battery chemistry as a discriminator in the selection process for a particularly type of battery, the development state of each of these technologies for this application is very low.
- (b) PFN and HV capacitors are not competitive from a weight standpoint. The system experts with whom these devices were discussed stated that for the most part, these systems are for terrestrial applications, and although they were eager to become involved in space applications, the development state of these technologies for this specialized application is very low.
- (c) Communication with the Space Power Institute at Auburn University indicates that the CDL technology is a much more acceptable approach than the PFN or HV, but there will still be a need for high-current switching, which will reduce the significant weight advantage of this technology. Although use of the CDL capacitor would considerably reduce capacitor weight over the PFN or HV, the Isuzu "Ultracapacitor" potentially offers a further order-of-magnitude improvement in weight, although very little information could be obtained to date on this device.
- (d) Because of their overall low state of technology development and readiness for these applications, no further effort was expended on high-energy capacitors in the course of these evaluations.

For the SRB application, according to a communication with KSC, the ELA system would replace the APU, fuel, and hydraulic system with its associated plumbing and actuators, all of which weigh approximately 2000 lb. The current ELA actuators are estimated to weigh 200-300 lb, therefore, the battery or battery/capacitor system which will replace the current APU/hydraulic system cannot weigh more than 1700-1800 lb. for an even or better weight trade. The battery system weights shown in the comparative sizing study of Tables 29 and 30 are based strictly on conversations with battery manufacturers. Furthermore, it is felt that these battery weights have been purposely increased substantially by the manufacturers (except in the case of Ni-H₂) in order to accommodate (1) the high rate discharge requirements, and (2) heat buildup in the battery during its operating time. Consequently, further work is needed to refine these battery weights and volumes before a definitive selection can be made.

For the battery types investigated, while present Ni-Cd batteries are relatively heavy, the metallic hydride technology promises twice the energy density of the Ni-Cd and would replace the Ni-Cd if perfected. However, it is still in development and not yet technologically ready. The Fiber-Nickel-Cadmium battery is currently in use in the aircraft industry, and while it does not increase the performance of Ni-Cd batteries, it significantly increases reliability. It should also be noted that the high-rate performance of a Ni-Cd battery is not as good as that of the lead-acid (Pb-PbO₂) type.

The silver-zinc (Ag-Zn) technology, on the other hand, is reliable, safe, and available now, with low complexity and excellent high-rate performance. Automatic activation for the Ag-Zn primary would add some weight and complexity (The electrolyte reservoir and activation system constitute approximately 40% of the weight of the battery system.). While the manually-activated Ag-Zn secondary is lighter than the primary, its high-rate performance is not as good.

The Bipolar Pb-PbO₂ technology has undoubtedly the highest current-carrying capacity pound-for-pound, and it is weight-competitive, with low complexity and high safety ratings. Its availability will depend on the results of the ongoing WPAFB/JCI technology program.

The CPV Ni-H₂ technology has presented this investigating team with further questions about its technology readiness and availability, which will depend on the results of technology programs in progress. The Ni-H₂ IPV technology is baselined for Space Station. Another major factor is that this type of battery is basically a high-energy-density, not a high-rate battery, it can be designed for high rates. Thus while it can be designed for such a launch vehicle application, it is felt that it may weigh considerably more than the manufacturer's claims.

Shuttle-Type Vehicles -- Evaluation and Results

During the summer of 1992, under a separate activity (NAG 9-626) [4], various power source and energy storage systems were studied as a possible replacement for the Space Shuttle Orbiter Auxiliary Power Unit (APU). The power and energy requirements for the existing Orbiter hydraulic system (Appendix A) [5] are in fact considerably more stringent than for an all-electric Orbiter (ELA application). This conclusion is also applicable to any unmanned Shuttle-derivative application. This is true because the power requirements for an alternate electrical power source to replace the current Orbiter APUs are based on keeping the present hydraulic system intact, and they assume the use of current flight rules and procedures. If, for example, electrical actuators were used and the hydraulic system were replaced with a system of electrical wires, controls, etc., the "base" power of 25-45 Hp per system to keep the hydraulic system pressurized to a nominal 3000 psia would largely be eliminated. The "pulse" power requirement of up to 105 Hp would remain, although it may not be as great with an all-electric (ELA) system.

For want of existing data, it was assumed for this study that the "base" power requirement for an ELA system would be 10% of the "peak" power required by the existing Orbiter APU system. This assumption is conservative but is still much less demanding than the "electric APU" requirement. Based on this assumption, Table 31 shows the derived energy requirements for a Shuttle Orbiter ELA system for the "design" mission case, which is the worst-case mission. The table includes energy values for two cases: (a) independent systems, e.g., batteries, in which each separate battery contains all the energy needed for each particular phase; and (b) the case of, e.g., fuel cells, where each fuel cell is sized for the appropriate power level, but the 3 fuel cells (which replace the 3 APUs) have a common energy source, i.e., their reactants come from a single tank. It is seen from this table that energy requirements for a Shuttle ELA system would thus probably be a maximum of 20-25 kWh at the power source. No further effort was expended on power and energy

requirements for the ELA applications due to the lack of real data for this case and the conceptual nature of the power systems considered. It is presumed that the energy requirements for an unmanned vehicle would be somewhat lower, because the unmanned system may not be burdened with requirements, e.g., "g" level, as stringent as those of a manned vehicle.

Assuming the energy requirements of Table 31, with a peak power level of 105 kW and a duty cycle of 10% as derived from Shuttle "electric APU" requirements, the following power/energy source system combinations were evaluated for the electric actuation application:

- (1) Existing Orbiter fuel cell with high-rate Ag-Zn primary batteries
- (2) High-Power-Density (HPD) fuel cell powerplants (FCPs)
- (3) All batteries (Ag-Zn)
- (4) Battery (Ag-Zn)-Flywheel combination

The selection of these system combinations is based on the original approach of the electric APU study, i.e., the concept of a "base" power system coupled with a "peak" system to handle the high-power transients [4]. The results of a weight optimization study for these combinations are as shown in Table 32.

In Table 32, all weights are for the power source only and do not include electrical wiring, electric actuators, etc. System weights do, however include integration penalties for mounting, cooling, and tankage and reactants in the case of fuel cells, and for mounting, cooling, and control electronics in the case of batteries and flywheels. Both single-system and three-system weights are shown in the table with the idea that similar to the present Orbiter design, three systems would probably be used for redundancy, unless sufficient redundancy could be designed in through crossover switching schemes between the vehicle electrical power system and the electric actuator power source, or between two ELA power sources. In these cases, further weight reduction would be achieved. For system combinations, e.g. fuel cell/battery or battery/flywheel, the linear programming system optimization program of Reference [4] was used to obtain optimized system weights. From this table it is seen that the use of Orbiter fuel cells for the base load in combination with high-rate silver-zinc primary batteries, or similarly, an all-battery system, would be extremely heavy compared to a battery/flywheel system or a system of high-power-density (HPD) fuel cell powerplants (FCPs). The latter would provide the greatest weight advantage due to its high specific power and specific energy. For a 60 kW HPD FCP weighing 322 lb. to produce the equivalent of 105 Hp peak at the electric actuator terminals, with a 33% FCP integration penalty for mounting, thermal control, etc., and 17 lb. of reactants (H_2 and O_2) to produce 20,900 Wh for an assumed worst-case mission, HPD FCP system specific power and energy are computed as follows:

$$P_{60\text{ kW HPD FCP}} = \frac{105 \times 0.746 \times 1000}{1.33 \times 322 + 17} = 189 \text{ W/lb or } 416 \text{ W/kg}$$

$$E_{60\text{ kW HPD FCP}} = \frac{20,900}{1.33 \times 322 + 17} = 47 \text{ Wh/lb or } 103 \text{ Wh/kg}$$

Since the reactant penalty is so small for this application, no tankage penalty is assessed, i.e., it is assumed that reactants will be supplied from the electrical power system (EPS) tankage system.

From Reference [4], p. B-3, the specific power and energy of silver-zinc primary batteries is:

<u>Type of Battery</u>	Battery Only		Battery Installed	
	<u>P (W/lb)</u>	<u>E(Wh/lb)</u>	<u>P(W/lb)</u>	<u>E(Wh/lb)</u>
Ag-Zn, 1 hr.	54.54	54.54	45.45	45.45
Ag-Zn, 2.5 hr.	34.09	55.45	28.41	46.21

For the Orbiter fuel cell powerplant (FCP) with its peak steady state power of 15 kW and peak energy production of 37,500 kWh (15 kWh for the 2 1/2 hour mission), using a 281 lb FCP weight, with the same 33% integration penalty and 17 lb of reactants, specific power and energy are computed as follows (again, no tankage penalty is assessed):

$$P_{\text{ORB FCP}} = \frac{15,000}{281 + 0.33 \times 281 + 17} = 38 \text{ W/lb or } 85 \text{ W/kg}$$

$$E_{\text{ORB FCP}} = \frac{37,500}{281 + 0.33 \times 281 + 17} = 96 \text{ Wh/lb or } 211 \text{ Wh/kg}$$

For the flywheel system, these same parameters are:

$$P_{\text{F/W}} = 909 \text{ W/lb or } 2000 \text{ W/kg}$$

$$E_{\text{F/W}} = 13 \text{ Wh/lb or } 29 \text{ Wh/kg}$$

Conclusions

For the launch vehicle case it seems obvious that batteries would be the preferred ELA power source, and that high-energy capacitors are not particularly attractive at this time due to their low state of development and the design difficulties of integrating them into a battery system from an operational standpoint. Although many types of batteries were investigated, the silver-zinc technology, based on its development state, performance, and consistent reliability since the days of Apollo, appears to have an overall advantage, even though it is not the lightest. Lithium batteries, while delivering the highest performance per unit weight, have an inherent safety problem as well as complex operational requirements such as the containment of toxic vent gases. The bipolar lead-acid technology shows perhaps the greatest promise from the standpoint of its high current-carrying capacity; however, the newer bipolar configuration is still in a developmental stage and therefore may not be as desirable as the silver-zinc technology, although there is room for debate when life-cycle and operational aspects are brought into the picture. Not enough data is available at present to evaluate these characteristics of the various battery systems.

For the case of Shuttle-type vehicles, Orbiter fuel cells, advanced (high-power-density) fuel cells, silver-zinc (primary) batteries and flywheels were investigated either singly or in appropriate combinations. The technology development state of these systems is discussed in Reference [4] of this report. System weight evaluations show that use of Orbiter fuel cells in combination with peaking Ag-Zn primary batteries results in the heaviest system. Similarly, an all-battery (Ag-Zn primary) system is also excessive in weight. The battery/flywheel system and the advanced fuel cell system are weight-competitive, and these systems are approximately 75% lighter than an all-battery or an Orbiter fuel cell/battery system, with the advanced fuel cell system showing a slight weight advantage. It must be remembered that much developmental work will be needed for either of these systems.

It should also be pointed out that regardless of the application (launch or Shuttle-type vehicle), the weight, complexity and cost of the electronic control system needed to operate any such system using batteries, fuel cells, or flywheels would be significant compared to the conversion system proper. For example, elaborate controls would be needed to operate a system of batteries operating in parallel for redundancy and load-sharing, coupled with flywheels for load-leveling.

Recommendations

It is recommended that before a system concept is adopted, further effort should be expended to:

- (1) gain more detailed information on power and energy requirements (ELA loads and load characteristics)
- (2) refine system weights and volumes (more indepth analysis of manufacturers' claims is needed)
- (3) investigate in more detail the state of technology readiness and availability of the systems of interest
- (4) conduct an analysis of thermal buildup in batteries, and a thermal control analysis for selected candidate systems
- (5) perform detailed analysis of electrical and electronic controls/conditioning/conversion methods and hardware
- (6) provide additional insight into the operational aspects of candidate systems

When the field is narrowed to a few or one system concept, an indepth system analysis and system simulation will be required to provide further design detail.

From a hardware standpoint, actuator system testing may be desirable to better define ELA characteristics (system simulation can be helpful here). Additionally, extensive component testing of power source prototype components, and ultimately a system-level prototype and/or engineering model test should be performed with at least simulated load characteristics.

References

- [1] Statement of work: "Peak Energy Storage Device Technology Evaluation for Electrical Actuator Applications," provided by NASA-JSC personnel May 1991.
- [2] "Evaluation of Actuator Energy Storage and Power Source Systems for Spacecraft Applications," NASA Grant NAG 9-561, Mid-Term Report, February 4, 1992.
- [3] "Twin Disk Composite Flywheel," by B. R. Ginsburg, Proc. of 17th Intersociety Energy Conversion Energy Conference (IECEC), Los Angeles, CA, August 1982.
- [4] "Investigation of Alternate Power Source for Space Shuttle Orbiter Hydraulic System," NASA Grant NAG 9-626, Final Report, Lamar University, Beaumont, TX, August 1992.
- [5] "Power and Energy Requirements for the Space Shuttle Orbiter Hydraulic System," provided by Mr. Bradley Irlbeck, NASA-JSC, May 1991.
- [6] Handbook of Batteries and Fuel Cells, edited by David Linden, McGraw-Hill Book Company, 1984.
- [7] "Electromechanical Actuator System for Shuttle Evolution; An Electrical Power System Design Study," by E.C. Darcy, J.T. Edge, B.J. Bragg, I.M. Hackler and M. Le, NASA Johnson Space Center, Houston, TX, AIAA-89-2520, 25th Joint Propulsion Conference, Monterey, CA, July 10-12, 1989.
- [8] Personal communication with Mr. David Miller, Eagle-Picher Electronics Division Joplin, MO, January 23, 1992.
- [9] Lithium Batteries, Jean-Paul Gabano, Academic Press, 1983.
- [10] "Battery Technology Status," January 2-3, 1991, unpublished data supplied by E. Kluksdahl, JSC/EP5 on January 8, 1992.
- [11] Technical Briefing, Popular Science, July 1991.
- [12] NASA Interoffice Memorandum from Mr. Paul March (Lockheed Corporation) to Ms. E.M. Kluksdahl, JSC/EP5, June 6, 1991.
- [13] Batteries for Space Power Systems, by Paul Bauer, National Aeronautics and Space Administration, NASA SP-172, 1968.

References (continued)

- [14] Personal communications with Mssrs. Robert Parker (primary batteries) and Curtis Brown (secondary batteries), Eagle-Picher Electronics Division, Joplin, MO, January 23, 1992.
- [15] Zinc-Silver Oxide Batteries, Edited by Arthur Fleischer, John Wiley and Sons, Inc., 1971.
- [16] Eagle-Picher data supplied by Mr. Bobby Bragg, NASA/JSC, January 8, 1992.
- [17] Yardney data supplied by Mr. Bobby Bragg, NASA/JSC, January 8, 1992.
- [18] Personal communication with Mr. Jeffrey Zagrodnik, Johnson Controls, Milwaukee, WI, January 23, 1992.
- [19] "Electric Vehicle Battery Applied to Aircraft," Mechanical Engineering, Vol. 114/No. 1, January 1992, p.22.
- [20] "Battery Aims to Solve Electric Vehicle Woes," Design News, November 4, 1991, p.24.
- [21] "NASA Aerospace Flight Battery Programs," NASA TM 103237, 25th IECEC, Reno, Nevada, August 12-17, 1990.
- [22] "Electric Vehicle Race Gathers Momentum," by Wesley R. Iversen, Design News, October 21, 1991, pp. 95-96.
- [23] Ibid, pp. 97-98.

Bibliographical Materials

- (1) "Sodium-Sulfur -- An Advanced Battery for Space," by Richard P. Sernka, Hughes Aircraft Company, AIAA Paper A90-18831, 1987.
- (2) NASA Interoffice Memorandum from Donald C. Brown, JSC/EH3 to E. M. Kluksdahl, JSC/EP5, "Concern From Haley Rushing re Lithium Batteries," January 27, 1992.
- (3) Personal communications with Messrs. Richard Rollins and Mr. Richard Straussner of High Energy Corporation, Parkersburg, PA, January 24, 1992.
- (4) Personal communication with Dr. Frank Rose, Space Power Institute, Auburn, AL, January 29, 1992.
- (5) Personal communication with Mr. Gale Sundberg, NASA Lewis Research Center, Cleveland, OH, November 14, 1991.
- (6) "High Density Double-Layer Capacitors for Energy Storage Applications," by J.-S. Lai and S. Levi, Tennessee Center for Research and Development, Knoxville, TN, and M.F. Rose, Space Power Institute, Auburn University, Auburn, AL, unpublished paper supplied by S. Fisher and E.M. Kluksdahl, JSC/EP5 on January 30, 1992.
- (7) "Double Layer Capacitors -- Scaleup from Small to Medium-Size Cells," by A.P. Trippe, Maxwell Laboratories, Inc., San Diego, CA, unpublished paper supplied by S. Fisher and E.M. Kluksdahl, JSC/EP5 on January 30, 1992.
- (8) ABC's of Capacitors, by William R. Mullin, Howard W. Sams & Co., Inc., Indianapolis, IN, 1978, p.89.
- (9) Capacitors - Their Use In Electronic Circuits, by M. Brotherton, D. Van Nostrand Co., Inc., New York, NY, 1959.
- (10) Power Capacitor Handbook, by T. Longland, T.W. Hunt, and W.A. Brecknell, Butterworths, Boston, MA, 1984.
- (11) Personal communication with Mr. Carey McClesky, KSC, February 3, 1992.
- (12) "Twin Disk Flywheel," by B. R. Ginsburg, 17th Intersociety Energy Conversion Engineering Conference (IECEC), Los Angeles, CA, August 1982.
- (13) "Low-Noise Spacecraft Attitude Control System," by V. Gondhalekar, J. R. Downes, D. B. Eisenhaure, R. L. Hockney, and B. G. Johnson, PA01-91, SatCon Technology Corporation, Cambridge, MA, 1991.

Bibliographical Materials (continued)

- (14) "Flywheel Energy Storage for Electromechanical Actuation Systems," by R. L. Hockney and J. R. Goldie, PA03-91, SatCon Technology Corporation, Cambridge, MA, 1991.
- (15) "Flywheels," by R. F. Post and S. F. Post, Scientific American, Volume 229, No. 6, pp. 17-23, December 1973.
- (16) Integrated Flywheel Technology 1983, NASA Conference Publication 2290, Proceedings of Workshop held at NASA Goddard Space Flight Center, Greenbelt, MD, August 1983.
- (17) Unpublished information on electric motor technology provided by Clifford Jacobs, Sundstrand Aerospace Division of the Sundstrand Corporation, Rockford, IL, July 1992.
- (18) "Study of Flywheel Energy Storage for Space Stations," Sidney Gross, Boeing Aerospace Company, Report No. D180-27951-1, Final Report on Contract NAS 9-16151, Mod 75, Seattle, WA, February 1984.
- (19) "Composite Flywheels: Status and Performance Assessment and Projections," A. P. Coppa and S. V. Kulkarni, Second European Symposium on Flywheel Energy Storage, Torino, Italy, May 1983.
- (20) "Assessment of Flywheel Energy Storage for Spacecraft Power Systems," G. E. Rodriguez, P. A. Studer, and D. A. Baer, NASA Technical Memorandum No. 85061, May 1983.
- (21) "Mission, Systems and Operations Analysis of NASA Space Station Freedom Advanced Concepts; Electrical Actuation Technology Bridging -- Interim Report No. 1," SSD91D0763, Rockwell International Corporation, Space Transportation Systems Division, October 15, 1991.
- (22) An Assessment of Integrated Flywheel Technology, NASA Conference Publication 2346, Edited by C. R. Keckler, R. T. Bechtel and N. T. Groom, Proceedings of Workshop held at NASA Marshall Space Flight Center, Huntsville, AL, February 1984.

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Table 1

Evaluation Criteria

-
- **Weight**
 - **Volume**
 - **Complexity (Including Integration)**
 - **Performance (Power, System Efficiency, Actuation Time, etc.)**
 - **System Safety (Reliability)**
 - **Technology Readiness (Availability)-Including Integration**
 - **Cost (Design, Development, Manufacture, Certification, Installation, Refurbishment*)**
 - **Vehicle Interface (for Existing Vehicles)**
 - **Operational Aspects**
 - **Initial Activation**
 - **Ground Operations (Servicing)**

* For reusable technologies

Table 2

Evaluation Approach

This study includes the evaluation of:

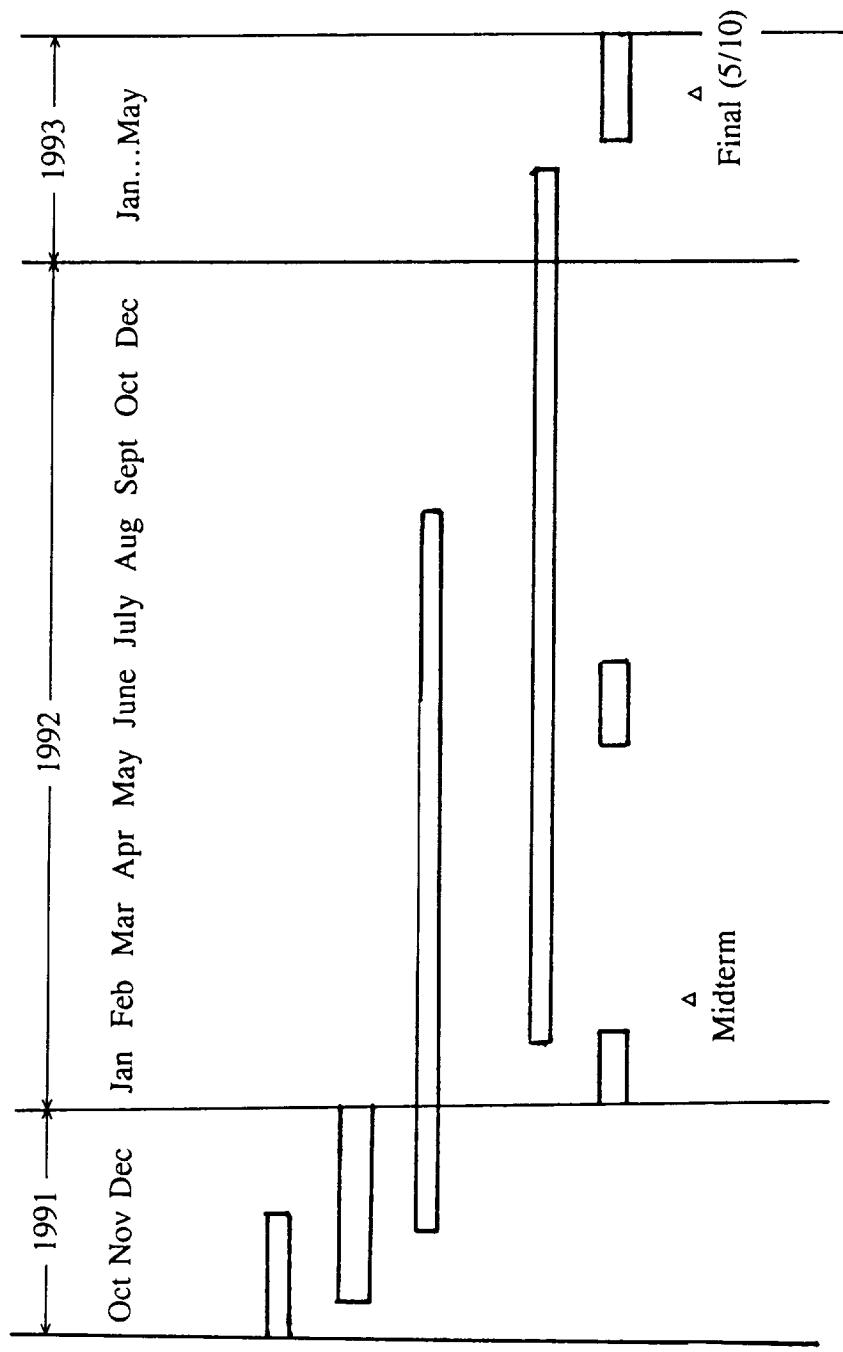
<u>Actuators</u>	<u>Energy Storage/Power Source Devices</u>	<u>Support Equipment</u>
Hydraulic	Batteries	Converters
<u>E</u> lectrical <u>A</u> cuation (ELA)	Fuel Cells	Diodes
	Flywheels	Power Conditioners
	Capacitors	Motors
	Accumulators	Tanks
		Charging Devices
		Pumps
		Lines
		Valves
		●
		●
		●

Table 3

Work Plan

- I. Literature Search and Data-Gathering
 - II. Identification of Spacecraft/Vehicle applications
 - Actuator Characteristics
 - Power System Requirements
 - III. Identification of Candidate Actuator/Energy Storage/Power Source Systems
 - System Descriptions
 - System Characteristics
 - IV. Evaluation of Candidate Systems Against System Requirements
 - System Trade Studies
 - Assessments Based on Evaluation Criteria
 - V. Documentation
 - System Descriptions
 - Discussion of Study Results
 - System Selection
 - Test Recommendations
-

Table 4
Schedule



- I. Literature Search/Data Gathering
- II. Spacecraft Applications
- III. Candidate System Definition & Evaluation
- IV. System Evaluations
- V. Documentation
- IV. Reports

Table 5

Team Assignments

W. E. Simon, Principal Investigator	Team Coordination NASA/Industry Interface Data "Leads" System Evaluation
F. M. Young, Co-Investigator	System Evaluation
J. Chang (GRA*)	Literature Search System Evaluation Graphics Support
D. Hou (GRA*)	Candidate Systems Definition (Fuel Cells, Batteries, Flywheels)
Y. He (GRA*)	Candidate Systems Definition (Capacitors, Accumulators) System Evaluation
A. Steppe (URA**)	Candidate Spacecraft/Vehicle Definition System Evaluation

* Graduate Research Assistant

** Undergraduate Research Assistant

Table 6
Contacts for ELA Study

- Akkerman, James, JSC, Shuttle Program Office (flywheel technology)
- Bragg, Bob, JSC (battery technology)
- Brown, Curtis, Eagle-Picher, St. Louis, MO (rechargeable silver-zinc batteries)
- Brown, Don, JSC (Technology Bridging Program)
- Eisenhaure, David B., President, SatCon Technology Corporation, Cambridge, MA (flywheel technology)
- Flake, Richard, WPAFB (advanced nickel-cadmium batteries)
- Harbison, John, MSFC (SRB operations, MSFC contribution to Technology Bridging Program)
- Irlbeck, Bradley, JSC, Power Branch (Shuttle power requirements)
- Jacobs, Clifford, Sundstrand Aerospace, Sundstrand Corporation, Rockford, IL (electric motor technology)
- Kluksdahl, E. M., JSC (ELA technologies, problem definition, contacts, battery technology)
- Lum, Benjamin, Rockwell International Corporation, Downey, CA (SRB power profile definition)
- McClesky, Carey, KSC (SRB and battery system operational information)
- Miller, David, Eagle-Picher, St. Louis, MO (lithium battery program)
- Parker, Robert, Eagle-Picher, St. Louis, MO (primary silver-zinc batteries)
- Pierce, Douglas, Johnson Controls, Inc. (bipolar and quasi-bipolar lead-acid batteries)
- Rose, Frank, Space Power Institute, Auburn, AL (chemical double-layer capacitors)
- Straussner, Richard, Consultant to High-Energy Corp. (pulse-forming network and high-voltage capacitors)
- Sundberg, Gale, LeRC, Cleveland, OH (launch vehicle requirements, high-frequency ac technology)
- Van Tassel, Keith, JSC, Power Branch (flywheel technology)
- Zagrodnik, Jeffrey, Johnson Controls, Inc. (CPV nickel-hydrogen batteries)

Table 7

Launch Vehicle and Spacecraft Applications

-
-
- SRB and Other Launch Vehicles
 - SRB
 - ALS/NLS (Advanced Launch System/National Launch System)
 - Heavy-Lift Vehicles
 - Shuttle-Type Vehicles
 - Existing Shuttle (manned)
 - Shuttle Derivative (Unmanned)
-
-

Table 8

Battery System Candidates for Launch Vehicle Applications

- Early focus on battery systems for launch vehicle applications

- 14 battery technologies evaluated:

Primary	Lithium - SOCl ₂
	- BCX
	- CFX

ZnO₂
Ag-Zn (Automatically Activated)

Secondary	Ag-Zn (Rechargeable)
-----------	----------------------

Advanced Ni-Cd

- FNC
- Metal-Hydride

CPV Ni-H₂

Ni-Fe

Na-S

Lithium-Iron Monosulfide

- Iron Disulfide
- Polymer

Hybrid Special Type	Lead Acid (Sealed Bipolar)/LiSOCl ₂ Hybrid
	Thermal Battery

Table 9

ELA Battery Evaluation

Battery Type (Technology): Lithium - SOCl_2 [6]

Description/Comments [7]

Li-SOCL₂ (Lithium Thionyl Chloride) chemistry offers the highest energy density and shelf life of battery systems flown to date. The lithium cells also have higher cell voltages than most other batteries (2.5 - 3.4 V).

Since the peak power required is at least 10 times the average power, a system of two batteries connected in parallel is proposed. One bipolar high-power-density battery and one monopolar battery optimized for high energy density.

The bipolar configuration can produce a peak current density of 200 mA/Cm₂. The bipolar configuration greatly lowers the internal impedance of the stack of cells, yet will not provide a high energy density. Nine 30 V dc modules in series would yield a 270V dc output. Each module contains 10 cells configured in a bipolar arrangement. The high-energy-density battery operates at 10 mA/Cm₂ in similar modular packages.

This system could be used to meet the high-energy-density requirement. Further development and test are required.

Advantages:

The Li-SOCl₂ cell has one of the highest energy densities of available battery systems. Energy densities can reach 500 Wh/kg and 900 Wh/l, the highest values being achieved with the large, high-capacity, low-rate cells. Long shelf life can be obtained (no leakage). Large batteries (270 V) can be manufactured [8].

Disadvantages:

Suitable for low to moderate rate designs but not suitable for high-rate designs. Difficult to fabricate in large quantities [8]. Safety concerns (when vented, 17 ppm lethal dosage has been experienced for cats) [8].

Availability:

Cells with capacities from 500 mAh to 20,000 Ah are available now.

Table 9 (Continued)
ELA Battery Evaluation

Battery Type (Technology): Lithium - SOCl₂, continued [6] [9]

Safety:

Originally suffered from a chemical instability that lead to an explosion hazard, especially on high-rate discharges and overdischarge, and a voltage delay that was most evident on low-temperature discharges after high-temperature storage. The anode, the solvent, and the electrolyte in lithium-oxyhalide cells all present potential hazards if allowed to contact with moisture and if inhaled. Low-rate cells have been used for several years. Recently safety has been improved with high rate and high-capacity cells.

Data: Li-SOCl₂

Cell voltage (V)	3.6
Operating temperature (°C)	-40 to 70
Energy density at 20°C (Wh/kg) (cylindrical size)	300 650
Discharge profile (relative)	Flat
Power density	Low to moderately high (depending on construction)
Shock resistance	Good
Approximate cost (\$/kwh)	250
Available capacity (Ah)	500 mAh - 15 kAh
Manufacturers	SAFT; GTE Sylvania Union Carbide Corp.

Centaur Program Li-SOCL₂ Battery Technology (4)

General Dynamics Battery Specifications (Spec. #57-06000 Rev. A)

- 9 Li-SOCL₂ active cells connected in series
- 250 Ah minimum capacity; 33.3 OCV maximum (3.7 V/cell)
- 74 lb maximum; 13.28" x 13.35" x 10.78"

Comment: Battery would weigh approximately 650 lb. for this application. However, for an SRB-type application, this type battery would not provide a high enough discharge rate (50-75 A maximum).

Table 10

ELA Battery Evaluation

Battery Type (Technology): Lithium BCX and CFX [8]

Description/Comments

As with all of the Lithium batteries, sufficiently high rates cannot be achieved to warrant more detailed investigation. Only possible application would be for base power in a hybrid (two-battery peak/base) application. Li-CFX batteries are currently in use on the NSTS Range Safety System.

Table 11

ELA Battery Evaluation

Battery Type (Technology): Zinc-Oxygen ($Zn-O_2$)

Description/Comments

A consortium of three corporations was formed to develop this technology for automotive application. The corporations are Dresbach Electromotive, Inc. (DEMI), Southern California Edison Co., and Arizona Public Service Co. A 45 kWh battery weighing 750 lb is being designed [11].

Advantages:

The principal advantage of this type of battery is its high energy density (up to 60 Wh/lb). It also has a high volumetric energy density, flat discharge voltage, long shelf life, no ecological problems, low cost, and a capacity independent of load and temperature when within operating range.

Disadvantages:

The two major development problems of this technology are growth of zinc dendrites during recharging, and CO_2 contamination of the potassium hydroxide electrolyte. These two problems have precluded the use of the Zinc-Air technology in a high-powered secondary battery application. However, significant progress has been made by DEMI recently relative to these two problem areas [12].

The $Zn-O_2$ battery is not independent of its environment. Flooding limits its power output, and dry-out limits its shelf life once opened to air. It also has a limited power output.

Data: $Zn-O_2$ (2)

Chemistry:

anode	Zn
cathode	O_2
electrolyte	KOH (aqueous solution)

Cell voltage (V) 1.5 - 0.9

Operating temp. ($^{\circ}C$) 0-50

Energy density (at 20 $^{\circ}C$)
(button size)

Wh/kg	290
Wh/l	905

Table 11 (Continued)
ELA Battery Evaluation

Battery Type (Technology): Zinc-Oxygen (Zn-O₂), continued

Discharge profile (relative)	flat
Power density	low
Storage temperature (C)	-20 to +25
Leakage	water transfer
Shock resistance	good
Major cells available:	To 560 Ah
Approximate cost (\$kwh)	1500
Manufacturers	Gould, SAFT
Safety	good

Secondary Zn-O₂ Batteries [6]

Work has been done in recent years on the zinc/air system as a candidate for electric vehicle propulsion. It has failed, however, to attract strong support because of low energy efficiency (about 40%), low operating voltage, and related chemical and operational difficulties. The development of an efficient high-rate bifunctional air electrode remains a formidable challenge. Two significantly different approaches have been taken in the development of large-capacity secondary zinc-air batteries. One approach, exemplified by systems pioneered by Sanyo, makes use of forced circulation of air and electrolyte. This system is perhaps the most advanced of metal/air batteries developed to date. Other approaches have been developed by Compagnie Generale d'Electricite (CGE) in France and Sony in Japan, based on circulating zinc slurry cells.

Specifications of 15V and 124V Sanyo Zinc/Air Battery systems:

	<u>15-V system</u>	<u>124-V system</u>
Battery voltage (V)	15 V (0.2 C)	124 V (0.2 C)
Capacity (Ah)	560	540 (130A max.)
Specific energy, wh/kg	116.5	109
specific energy, wh/l	99	c. 100
weight, kg	70	565
Cycle life	200-300	200-300
Dimensions (LxWxH),mm	560x330x384	1550x1050x334

The Compagnie Generale d'Electricite development culminated in a demonstration of a 12- to 14-kw system, but it has not been made commercially available.

Table 12

ELA Battery Evaluation

Battery Type (Technology): Silver-Zinc (Ag-Zn)

Description/Comments [13] [14] [15]:

- Silver-zinc batteries are one of the battery technologies which have received much support from NASA over the years, (others are nickel-cadmium, silver-cadmium, and the class of batteries which uses organic solvents). NASA has also supported studies of other batteries, such as lead-acid and ammonia, in fundamental chemistry and aspects of battery technology such as charge control.
- The silver-zinc technology was used extensively in the Apollo program as a high-rate primary battery, and this technology has not changed much since these early applications (performance is still limited by the separator system). Remotely activated primary silver-zinc batteries would have to have the electrolyte in a separate container, and this electrolyte would be transferred into the cells by remote activation shortly before launch. A bipolar design would have the same electrical performance as the standard cell hookup, but would result in lower weight and volume.

For use as secondary batteries, special separators are added to the silver-zinc system to delay the internal deterioration process so that the battery has a long life (wet stand) of approximately 1 year. The rechargeability is also improved, with approximately 10 deep discharges, or 500 shallow discharges, permitted due to the addition of multiple layers of separators. These batteries have relatively high energy density. High-current performance is inferior to that of the primary silver-zinc battery, but this may not be important for its intended use.

Work done at WPAFB several years ago on bipolar secondary silver-zinc batteries addressed mechanical problems (sealing, which caused leaks between the cells and resultant shorting), and problems with recharging (venting gas from the cells). The result of this work was that while these problems were manageable for single-cell operation, they could not be adequately solved when multiple cells were joined to form a complete battery. For these reasons it appears at the present time that a primary silver-zinc battery would be preferable to a secondary. These batteries were/are used in the Shuttle program (as OFI/DFI batteries, and as a backup for the range safety system). They are shipped dry and activated at the launch site (reserve-type).

Performance for these applications is generally excellent except for the relatively high internal heat generation caused by discharge of divalent silver oxide at the voltages of the lower plateau. For short-term applications (e.g., SRB), this problem is not serious since the primary battery would not be reusable, so that heat can be allowed to build up internally with no cooling required.

Table 12 (Continued)
ELA Battery Evaluation

Battery Type (Technology): **Silver-Zinc (Ag-Zn) (continued)**

Advantages:

This technology (Ag-Zn primary) is available now - many batteries have been built and tested. Miniature to massive size batteries are available (0.3 to 300 Ah).

High-rate high-energy-density (90-100 "C") easily attainable
5-30 Wh/lb depending on rate
Good voltage regulation
Manual or remote activation available
Extended dry shelf life (sealed package)
Good charge retention
High environmental tolerance
Cost not prohibitive

Disadvantages:

One of the only disadvantages which could be discerned with this type of battery is that if it is remotely activated just prior to launch, there is not way to tell beforehand if a particular battery will have a problem. About the only way to work around this problem is to build confidence in the design through extensive testing, and perhaps to increase the redundancy over and above that level used to satisfy operational failure criteria.

Performance Characteristics

REMOTELY ACTIVATED PRIMARIES [16]

Remote initiation can be either electrical or mechanical (also available as inertially activated). These systems contain high-pressure diaphragms (100 psi burst pressure) with no moving components. When the battery is activated, the expanding gas distributes the electrolyte, then sweeps the manifold clean of electrolyte, returning the battery to equilibrium. There are no differential pressures to maintain, and the entire battery system is enclosed in a single integrated and potted unit.

Cell

Open circuit cell voltage: 1.6 to 1.87 V
Working voltage: 1.2 to 1.55 V

Battery

Operating temperature (°F): -20 to +160
Heater-assisted: -65 to +160
Energy Density (Wh/lb): 5 to 30
(wh/cu. in.): 0.4 to 3.5

Table 12 (Continued)

ELA Battery Evaluation

Battery Type (Technology): **Silver-Zinc (Ag-Zn) (continued)**

MANUALLY ACTIVATED PRIMARIES (HI-RATE) [16]

Cell

Open circuit voltage (V):	1.6 - 1.87
Working voltage (V):	1.3 - 1.55
Voltage Regulation:	± 2% under fixed conditions (maximum voltage regulation achieved at 100 msec or less)

Battery

Energy density (Wh/lb): (Wh/cu. in.):	25 - 35 1.7 - 3.2
Operating temperature (°F):	-40 to +130 (-65 with heater)
Storage temperature (°F):	-65 to +125 dry -40 to +100 wet
Shock (mechanically, typical):	100 g's
Vibration (typical):	200 g's, 5-2000 Hz
Acceleration (typical)	100 g's
Attitude	50,000 nominal (constructed or modified for any altitude)
Position	Any axis
Life Expectancy	
-Shelf, dry	2-5 years
-Shelf, wet	15-30 days
-Cycle	1-5
-Charge Retention	90-100% of nominal after 15-day wet stand

RECHARGEABLE (SECONDARY) SILVER ZINCS (HIGH-RATE) [17]

Over 30 rechargeable models (HR-01 to HR-200) available, with nominal 60-minute discharge rates from 0.1A to 200 A (nominal 20-70 Wh/lb and 1.25 - 5.3 Wh/cu. in.).

Table 13

ELA Battery Evaluation

Battery Type (Technology): Advanced Ni-Cd [6]

Description/Comments

Advanced nickel-cadmium batteries are presently receiving considerable attention from NASA, together with the nickel-hydrogen technology, for planned secondary battery applications.

The sintered-plate nickel-cadmium battery is a more recent development of the cadmium system, having a higher energy density (up to 50% greater than the pocket construction). In addition, because the sintered plate can be constructed in a much thinner form than the pocket plate, the cell has a much lower internal resistance and gives superior high-rate and low-temperature performance. A flat discharge curve is the characteristic of this type of battery, and its performance is less sensitive than other battery systems to changes in discharge load and temperature. The sintered-plate battery has most of the favorable characteristics of the pocket-type battery, although it is generally more expensive. It is electrically and mechanically rugged, is very reliable, requires little maintenance, can be stored for long periods of time in a charged or uncharged condition, and has good charge retention. Cells losing capacity through self-discharge can be restored to full service with normal charge. For these reasons, vented sintered-plate nickel-cadmium batteries are used in applications requiring high power discharge such as in aircraft turbine engine and diesel engine starting as well as other mobile and military equipment. The battery provides outstanding performance where high peak power and fast recharging are required. In many applications, the vented sintered-plate battery is used because it leads to a reduction in size, weight, and maintenance as compared with other battery systems. This is particularly true in systems subject to low-temperature operation. The rise in battery voltage at the end of charge of the vented cell also provides a useful characteristic for controlling the charge.

Advantages:

Flat discharge profile; higher energy density (50% greater than pocket-plate); superior high-rate and low-temperature performance (-10°C to +10°C normally; can get -40°C to +50°C); rugged; little maintenance required; capacity can be restored after self-discharge; long cycle life (30,000 cycles); good deep-discharge tolerance (very accommodating to overdischarge and overcharge).

Disadvantages:

High cost; "memory effect"; controlled charging system required to prevent "thermal runaway." Cell quality and reliability are still major concerns of this technology. Also, cadmium is considered a hazardous material. Most experience to date has been with aircraft applications.

Table 13 (Continued)

ELA Battery Evaluation

Battery Type (Technology): Advanced Ni-Cd [6] (continued)

Safety [6]:

Due to its structural integrity, the sintered plate is practically indestructible in all normal and most abnormal operating situations. The cell component which accounts for the overwhelming majority of all vented sintered nickel-cadmium cell failures is the cellophane gas barrier. Failure of the gas barrier results in an effective chemical "short-circuit" of the overcharge current through the action of oxygen recombination. "Memory effect" and "thermal runaway" must also be considered. Potential hazards such as gas fire and or explosion, arcing and burning, corrosive KOH, and electric shock must also be accounted for in system design [6].

Other characteristics:

The state of charge is known very directly and accurately. This type of battery essentially operates like a primary battery; it can be checked out up-front, and charging may be easier than with other types. It will achieve approximately 55 Wh/kg for this application. It should be noted that the nickel-metal hydride variation has less power capability. Also, in general, advanced nickel-cadmium batteries will cost more than other types.

Availability

Typical vented sintered-plate nickel-cadmium cells have rated capacity (1-h rate) of 14-80 Ah

Maximum power at 25°C (W): 260-1250
 0.61-3.1

Energy/power density:

Typical average values for the energy and power densities of the vented sintered-plate nickel-cadmium cell at 23°C are:

Capacity density (single cell, 1-h rate)	25-31 ah/kg 48-80 Ah/l
Storage	-60°C to +60 °C
Energy density (1-h rate)	30-37 Wh/kg 58-96 W/l
Power density (at maximum power)	330-460 W/kg 730-1250 Wh/L
cell voltage V	1.3-0.9

Table 13 (Continued)

ELA Battery Evaluation

Battery Type (Technology): Advanced Ni-Cd [6] (continued)

SECONDARY Ni-Cd BATTERIES

The Ni-Cd battery has the highest survivability and longest cycle life and is therefore often used as a secondary (cycling) battery, especially in long-life applications even though it is heavier than the silver-cadmium battery. Improvements in this cell have been the development of inert separators and more reliable seals.

FIBER-NICKEL-CADMIUM (FNC) TECHNOLOGY

New Fiber-Nickel-Cadmium (FNC) battery developed for electric vehicles is proving to be more durable than conventional batteries and is seeing increasing use in the aerospace industry. This sealed design, manufactured by Advanced Energy Systems Division of Acme Electric Corporation, Tempe, AZ has been in service longer than one year on five Israeli Air Force F-165 with no maintenance. At 100% DOD, FNC gets 2000 cycles (2 x Lead-Acid battery) [19].

Table 14

ELA Battery Evaluation

Battery Type (Technology): Metal-Hydride

Ovonic Battery design [20]: new metal-hydride battery.

Description/Comments:

Sealed; greater energy density -- twice that of Ni-Cd cells. Similar to a Ni-Cd battery, but metal hydride replaces Cd as the negative electrode. Uses an alkaline electrolyte (KOH), as does Ni-Cd.

Advantages:

Battery is completely sealed (as compared to Ni-Fe)

Greater energy density (approximately 2 x Ni-Cd)

Long life ("life of car" in automotive application)

Disadvantages:

Manufacturability is a potential issue

Materials problems in early development (limited life); however, a sintered electrode was produced from the new metal hydride material (alloy) with sufficient bonding strength to resist corrosion in the battery environment.

Performance Characteristics:

60-75 Wh/kg

Table 15

ELA Battery Evaluation

Battery Type (Technology): Nickel-Hydrogen

Description/Comments:

At the present time NASA and WPAFB are expending considerable effort on the Ni-H₂ technology, in particular the common-pressure-vessel (CPV) non-bipolar type (Johnson Controls, for WPAFB) and the CPV bipolar design (LeRC). The major goal of the NASA work is to develop a NASA Standard Ni-H₂ cell [21]. Development problems to date include the catalyzed-wall effect (at 26% and 31% KOH concentration), and flaw growth in the cell cases. The sealed Ni-H₂ secondary battery is actually a hybrid technology combining battery and fuel cell technologies.

Advantages:

High energy density; long cycle life, even with deep discharge; cell can tolerate overcharge and reversal; state of charge indicated by hydrogen pressure.

Disadvantages:

High initial cost; self-discharge proportional to hydrogen pressure.

Performance Characteristics:

Over 6000 deep-discharge cycles obtained

Energy density: 60 wh/kg

50-860 Wh/L

Cell voltage (V): 1.3-1.1

Most figures of merit are similar to Ni-Cd in current practice; however, this technology holds the promise of higher energy density and longer life.

Table 16

ELA Battery Evaluation

Battery Type (Technology): **Nickel-Iron (Ni-Fe)**

Description/Comments [22]:

Latest effort on this technology is Chrysler/EPRI Program for Chrysler's TE Van electric vehicle. Considered by some technologists as next viable step beyond lead-acid batteries. Chrysler plans to use 6V NIF 200 series nickel-iron modules from Eagle-Picher Industries. A pilot production plant is to be built with initial capacity for 500 nickel-iron EV batteries per year (planned for 1993).

Advantages [22]:

Higher specific energy
Potential for achieving twice the energy density of lead-acid
Rugged
Long life

Disadvantages [22]:

Not as far along developmentally as other types (e.g., lead acid)
High initial cost (three times as much as lead-acid)
Cannot be sealed (required water injection)
Rechargeable type requires gas removal system to remove hydrogen generated during recharge

Performance Characteristics:

Potential for up to 50 Wh/kg

Table 17

ELA Battery Evaluation

Battery Type (Technology): Sodium-Sulfur (Na-S)

Description/Comments:

Ford/CSP-UK is building a demonstration EV fleet (70-100 vehicles) with 40 kWh Na-S battery packs (336V) for a 30-month demonstration phase, for European Escort Van (70-100 75 hp vehicles beginning in 1992). Technology relies on molten sodium and sulfur electrodes [21].

The sodium-sulphur (Na-S) battery is a high-energy-density, long-life secondary (rechargeable) battery being developed for use in the commercial and military sectors. These batteries are efficient energy storage systems that are fabricated from inexpensive, commonly-available materials using relatively simple processes. The batteries exhibit exceptional power at deep discharge, and long term stability compared to other battery systems [22].

Advantages [23]:

High Energy Density (see performance characteristics below)

Reasonable power at approximately 140 W/kg

Constructed of low-cost materials

Disadvantages [23]:

Farther from commercial production than Ni-Fe

High operating temperature (662-715F) - safety concern and potential corrosion problem

Potential for fire or explosion - requires that battery be heavily encased for safety and ruggedness (could double battery pack weight - packaging challenge).

Needs internal heater to maintain battery temperature (keep electrolyte molten) when battery is not in use.

Battery life approximately 18 months (based on EV usage profile)

Present Cost approximately 4 x Ni-Fe

Performance Characteristics:

Potential to achieve 100 kW/kg (3 x Lead-Acid)

Table 18

ELA Battery Evaluation

Battery Type (Technology): **Lithium-Iron Monosulfide**

Description/Comments:

For the SRB application, Lithium batteries do not possess sufficient high-rate capability, compared to other high-rate batteries such as silver-zinc, to warrant further indepth investigation at this time. Additionally, based on temperature data from the SRB aft skirt projected to an NLS application [4], there would be safety concerns with Lithium batteries in this environment. Admittedly these heating problems could be alleviated with shielding, and active cooling if necessary, but these fixes would result in increased weight and volume.

Table 19

ELA Battery Evaluation

Battery Type (Technology): Lithium-Iron Disulfide

Description/Comments:

Ibid. Lithium-Iron Monosulfide

Table 20

ELA Battery Evaluation

Battery Type (Technology): Lithium Polymer

Description/Comments:

Ibid. Lithium-Iron Disulfide

Table 21

ELA Battery Evaluation

Battery Type (Technology): Lead Acid (Sealed Bipolar)/LiSOCl₂ Hybrid

Description/Comments:

- Lead-acid (Pb-PbO₂) batteries are well established for their high power capacity. The system proposed uses this chemistry for the high-power task while retaining the Li-SOCL₂ chemistry for the high-energy-density requirement.

- USAF/JPL is developing a sealed bipolar lead-acid battery to achieve a pulse power density greater than 4 kW/kg for SDIO. The battery has a sealed design with oxygen recombination. Several battery configurations have been built, each optimized to pulse durations of 1, 5, 10, and 100 seconds.

10 s for EMA, 4% DOD in EMA application.

peak current density 1000 mA/cm² at 90 V dc

3 modules connected in series are required to meet 270 V dc.

5 year life is expected (at the depth indicated above)

Lead-Acid Bipolar performance: 6-18 Wh/lb

Preliminary conclusion:

The Lead Acid Bipolar technology could be used to meet the high power pulse requirements; further test and development are needed. Most battery technologists do not favor a hybrid battery system such as the system described above (Bipolar Lead Acid/LiSOCl₂), but prefer a single high-rate battery which can handle both base and pulse power requirements.

Table 22

ELA Battery Evaluation

Battery Type (Technology): Thermal Battery

Description/Comments: [4]

This type of battery is designed to be ignited by a pyrotechnic which creates rapid heat buildup, melting the electrolyte (a nonconductive solid at ambient temperature). The electrolyte then becomes conductive, permitting the battery to deliver high power for short times.

Advantages:

Long preactivation (shelf) life -- greater than 10 years (some to 20 years)

Operational life -- seconds for high-power pulse batteries to more than 1 hour for suitably insulated designs

"Instant" activation (tens of milliseconds)

High peak power exceeding 10 W/cm²

Very high demonstrational reliability and ruggedness following long-term storage at extremes of ambient temperature

Extremely resistant to shock, vibration, acceleration and/or spin

No maintenance or servicing required

Hermetically sealed

Many cell configurations available

Disadvantages:

Not rechargeable (like a primary, or reserve battery)

High thermal buildup (requires special insulation)

Low power (< 1 kW)

Performance:

Low power (< 1 kW)

Energy density to ~ 30 Wh/kg

Lithium anode thermal batteries show an order-of-magnitude performance improvement over conventional thermal batteries

Table 23
ELA Battery Evaluation Sheet

Battery Type (Technology): Automatically Activated Ag-Zn (Primary)

Description/Comments:

Primary Ag-Zn technology has firm technology base from Apollo Program
Performance has not changed much over the years
Remotely activated, bipolar available
Excellent performance except for relatively high internal heat generation

Advantages:

High-rate, high-energy-density, primary battery
Available NOW -- many batteries have been built and tested (miniature to massive sizes: 0.3 to 300 Ah)
Good voltage regulation
Extended dry shelf life (sealed package)
Cost not prohibitive

Disadvantages:

Separate electrolyte reservoir and activation system (~40% of total system weight)
No way to tell charge if activated just prior to launch

Performance: Energy Density: 5-30 Wh/lb
0.4-3.5 Wh/in³

Table 24
ELA Battery Evaluation Sheet

Battery Type (Technology): Manually Ag-Zn (Secondary)

Description/Comments:

Considerable development work at WPAFB
Separator design is different from primaries

Advantages:

Over 30 rechargeable models available (HR-01 to HR-200) with nominal 60-minute discharge rates from 0.1 A to 200 A

Disadvantages:

High-current performance is inferior to Ag-Zn primaries
Seal problem, problems with recharging (cell vent)
Relatively high internal heat generation

Performance: Energy Density: 20-70 Wh/lb
1.25-5.3 Wh/in³

Table 25
ELA Battery Evaluation Sheet

Battery Type (Technology): Bipolar Pb-Acid

Description/Comments:

Well established technology, particularly high-rate application
USAF/JPL developing sealed bipolar Pb-Acid battery for extended high-rate (SDIO) application, for varying pulse durations from 1 to 100 seconds

- Quasi-bipolar available now, expensive, made by hand
- True bipolar better (would cut mfg-steps from 25 to 3-4); 30% weight savings (replaces lead with plastic); 30% vol. savings

WPAFB/JCI effort currently underway for true bipolar development

Advantages:

Excellent high-rate performance (probably best of all candidate technologies)
Ongoing development program (excellent results to date)

Disadvantages:

**Additional development required for bipolar
Venting of gases**

Performance: Energy Density: 6-18 Wh/lb
1-3 Wh/in³

Table 26
ELA Battery Evaluation Sheet

Battery Type (Technology): **CPV Ni-H₂**

Description/Comments:

Considerable development effort by NASA and WPAFB
Most experience to date with aircraft applications (IPV)
Heavier if not bipolar, and lower rate

Advantages:

High energy density/high rate
Good tolerance of overdischarge and reversal
State of discharge indicated by hydrogen pressure
Navy work for satellite (first launch 1992)

Disadvantages:

High initial cost
Self-discharge proportional to hydrogen pressure
Requires additional development for high-rate application (Bipolar-LeRC)
High-pressure hydrogen in SRB thermal environment may be a safety problem
Potential heat rejection problems
Self-discharge problem

Performance: Energy Density: 15-25 Wh/lb
 0.2-0.5 Wh/in³
TESS (Transporter Energy Storage System) (5-7 Wh IPV)

Table 27
ELA Battery Evaluation Sheet

Battery Type (Technology): Advanced Ni-Cd or "Super Ni-Cd" or "Super Ni-Cd"

Description/Comments:

Ongoing NASA program for high-rate, high-energy-density, low temperature battery
Substantial technology advance with sintered-nickel design
Most experienced to date with aircraft applications
New fiber-nickel-cadmium (FNC) technology for electric vehicles is promising
(increased reliability/ruggedness)

Advantages:

- High energy density
 - Long cycle life
 - Good deep-discharging tolerance
 - Rugged (Maintenance-free, based on extensive aircraft operation)
 - Flat discharging profile
 - Known state of charge
 - Can be reconditioned to extend life

Disadvantages:

- Not as good as Pb - PbO₂ and Ag-Zn for high-rate operation
High cost
"Memory" effect
Controlled charging required to prevent thermal runaway
Cell quality and reliability are still major concerns
Cadmium is considered a hazardous material (possibly could use metallic hydride cell-energy density 2 x Ni-Cd)

Table 28
ELA Battery Evaluation Sheet

Battery Type (Technology): Metal-Hydride

Description/Comments:

Made by Ovonic Battery Co.; configuration is similar to Ni-Cd

Advantages:

Sealed

Low cost

High energy density (2 x Ni-Cd)

Quick recharge (1/32 that of Pb-PbO₂)

Disadvantages:

Still in early development

Manufacturability is a key issue

Performance: Energy Density: 30-40 Wh/lb
2-4 Wh/in³

Table 29

**Comparison of Selected Battery
Technologies for SRB Application**

Type	Wh/lb DM*	Wh Size	Wh/in ³	Battery Weight (lb)	Battery Volume (in ³)
Automatically Activated Ag-Zn	P	15	13.5	15,625	1.5-2.0 600-650 (625) 7,500-10,800 (10,000)
Manually Activated Ag-Zn	S	25	10	11,600	1.75-2.0 400-500 (465) 5,000-7,150 (6350)
Bipolar Pb-Acid	P	9	3	3,480	1.0-2.0 250-425 (385) 1,500-5,100 (4370)
CPV Ni-H ₂	S	20	5	5,800	2.3-2.8 240-285 (250) 2,100-2,500 (2,200)
Advanced Ni-Cd	S	(10-15)	13.4	15,544	2.7-4.6 780-870 (820) 2,350-6,150 (4,270)

* P (Primary); S (Secondary)

** Design Margin (equivalent energy oversizing recommended by manufacturers) imposed on SRB total energy requirement (1160 Wh)

Table 30 (Continued)

**Comparison of Selected Battery
Technologies for SRB Application (continued)**

Type	Battery Wt.(lb)	Battery Vol. (in ³)	Complexity*	Safety*	Technology Readiness*
Automatically Activated Ag-Zn	P 625	10,000	L-M	H	H (Available Now)
Manually Activated Ag-Zn	S 465	6,350	L	H	H
Bipolar Pb-Acid	P,S 385	4,370	L	H	M
CPV Ni-H ₂	S 250	2,200	M-H	M	M
Advanced Ni-Cd	S 820	4,270	M	H	M
• FNC	S 820	~4,270	L	H	H (Available Now)
Metal Hydride	S 410	~4,270	L	H	L

* H=High, M=Medium, L=Low .

Table 31

Derived Energy Requirements for Shuttle Orbiter ELA System

"DESIGN" MISSION

Mission Phase	Time (min.)	Total Energy (kWh) Independent System	Total Energy (kWh) Common Energy Source (Reactants)
Ascent	28	4.7	4.7
FCS Checkout	12	2.0	0.7
Pre-Entry	42	4.7	1.6
Entry	68	11.4	11.4
TOTAL	150	22.8	18.4

Note: For total ("Base" + "Pulse") energy requirements for system sizing, add 2.5 kWh max. to above, i.e., independent Base/Pulse System = 25.3 KWh Total, with Common Energy Source = 20.9 KWh Total

Table 32

**Results of Weight Optimization Study for Shuttle and Shuttle-Derivative
Electrical Actuation (ELA) Power Source Systems**

<u>Case</u>	<u>System</u>	<u>Single System Weight (lb)</u>	<u>Weight of 3 Systems (lb)</u>
1	Orbiter FCP with High-Rate Ag-Zn Batteries (Primary)	2110	6330
	1-Orb FCP 514		
	<u>Ag-Zn Batt</u> <u>1596*</u>		
	Total 2110		
2	High-Power-Density FCP System	445	1335
3	All-Battery System (Ag-Zn Primaries)	1981	5943
4	Battery/Flywheel System	512	1536
	Flywheel 83		
	<u>Ag-Zn Prim. Batt.</u> <u>429**</u>		
	TOTAL 512		

* 1463 lb 1-hr discharge Ag-Zn Primary, with 133 lb 2.5-hr discharge Ag-Zn primary

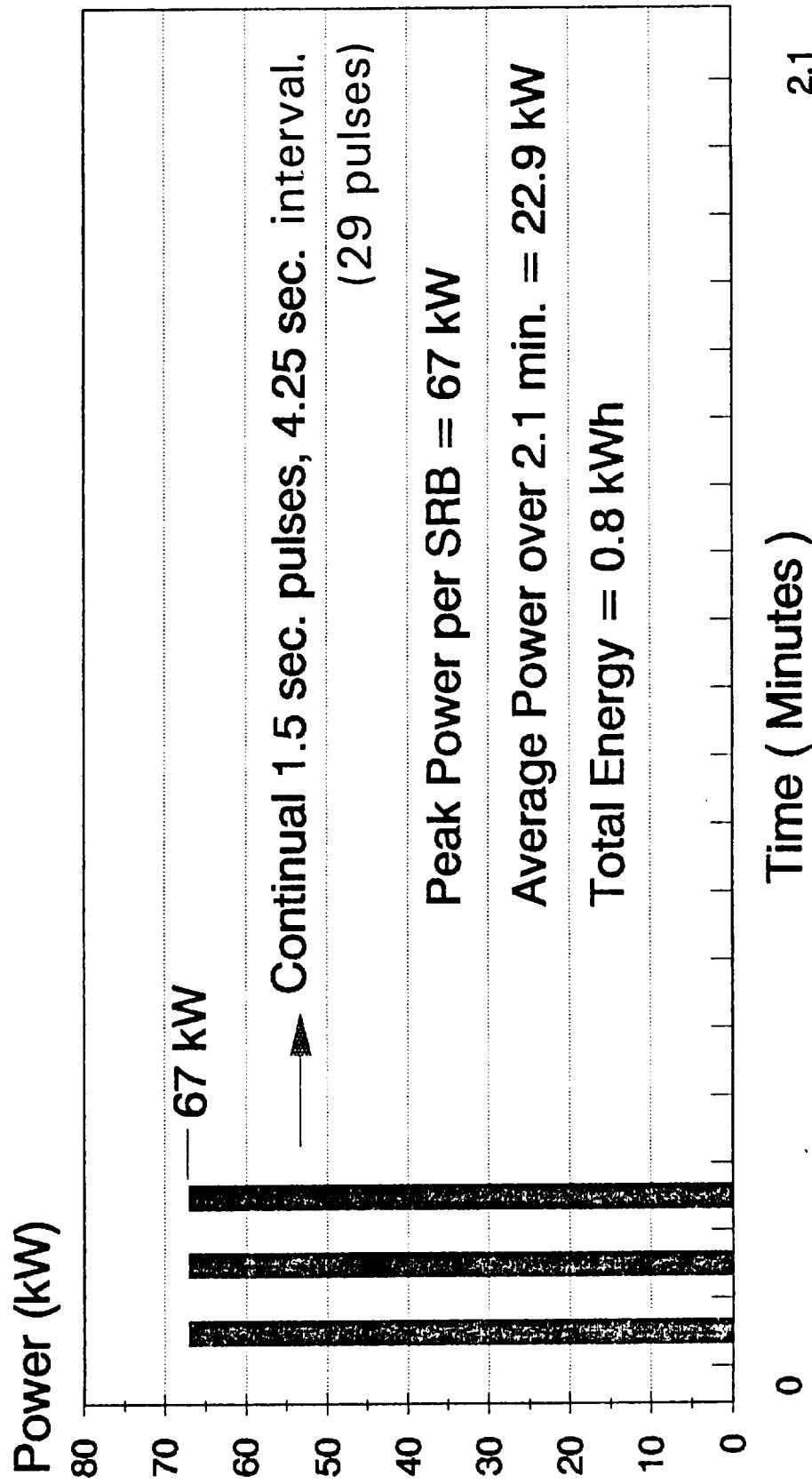
** All 2.5-hr discharge Ag-Zn primary

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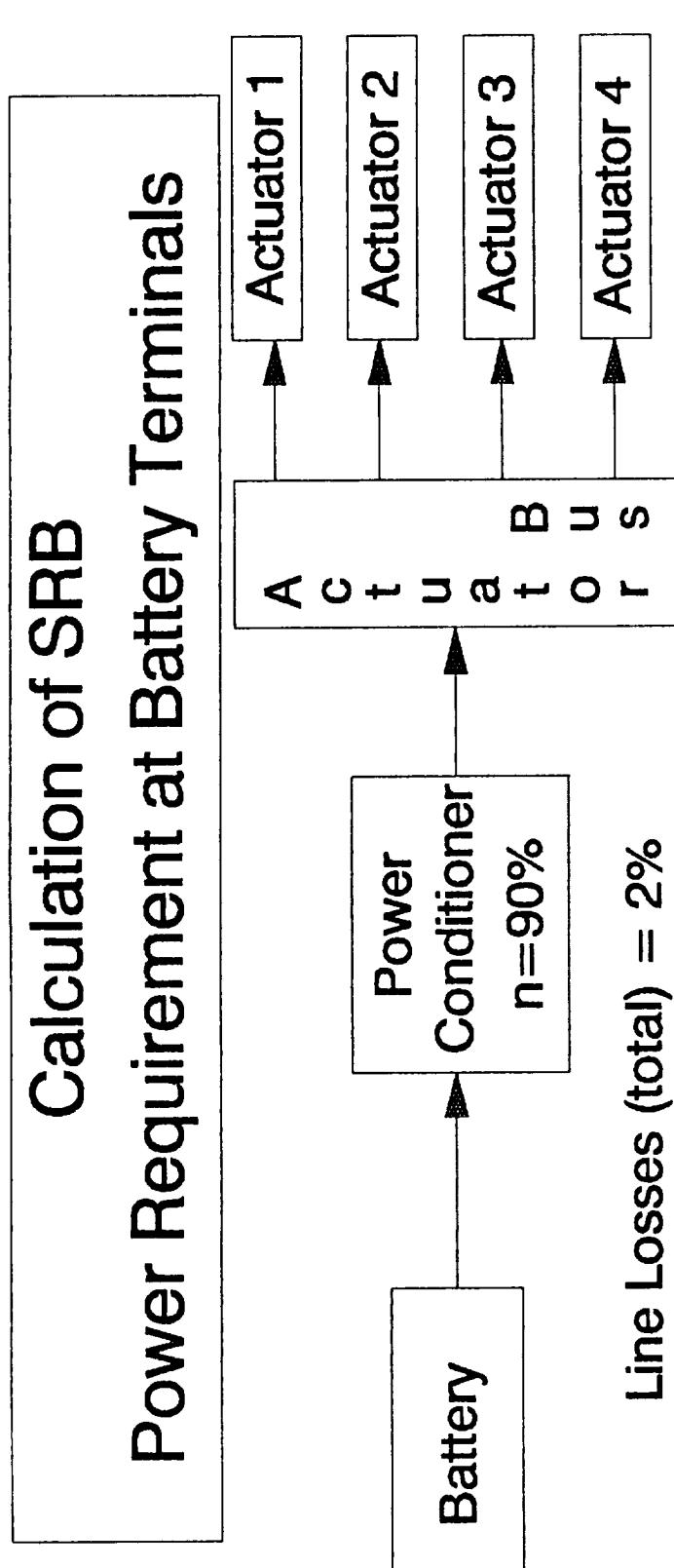
Figure 1

SRB Actuator Bus Requirement (each SRB)



- (1) Source is 10/15/91 presentation modified by
01/13/92 telecon with B.T.F. Lum
and C.L. Pond of Rockwell International Corporation.

Figure 2

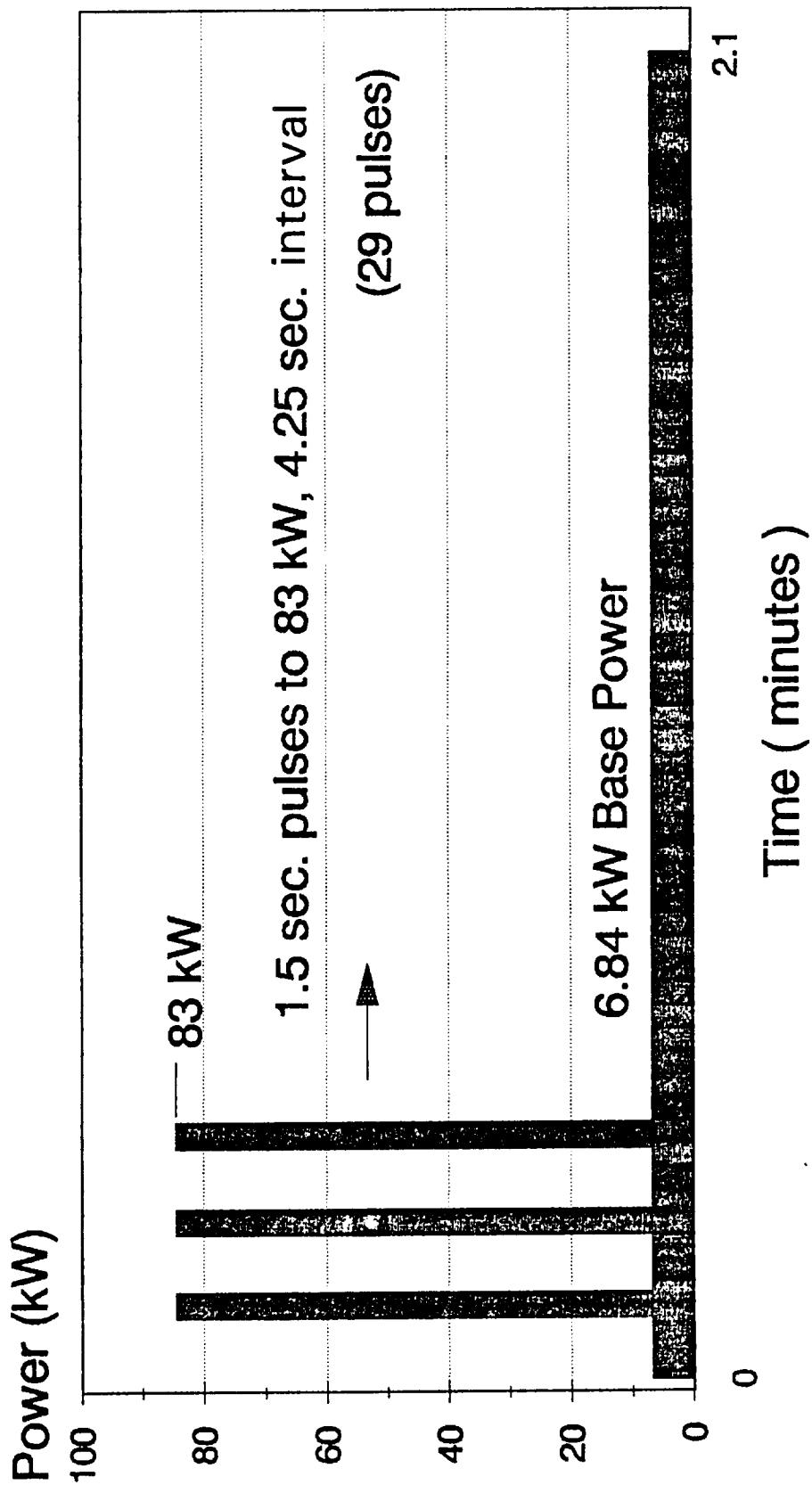


$$P_{\text{batt peak}} = \frac{P_{\text{base}} + P_{\text{act pulse}}}{0.98 \cdot 98 \times .90} \quad \text{Conditioner Base Load} = 10\% \text{ of peak}$$
$$= 6.84 + 76.13 \quad P_{\text{act peak}} = 67 \text{ kW}$$

$$P_{\text{base}} = 6.7 \text{ kW}$$
$$P_{\text{batt peak}} = 83 \text{ kW}$$

Figure 3

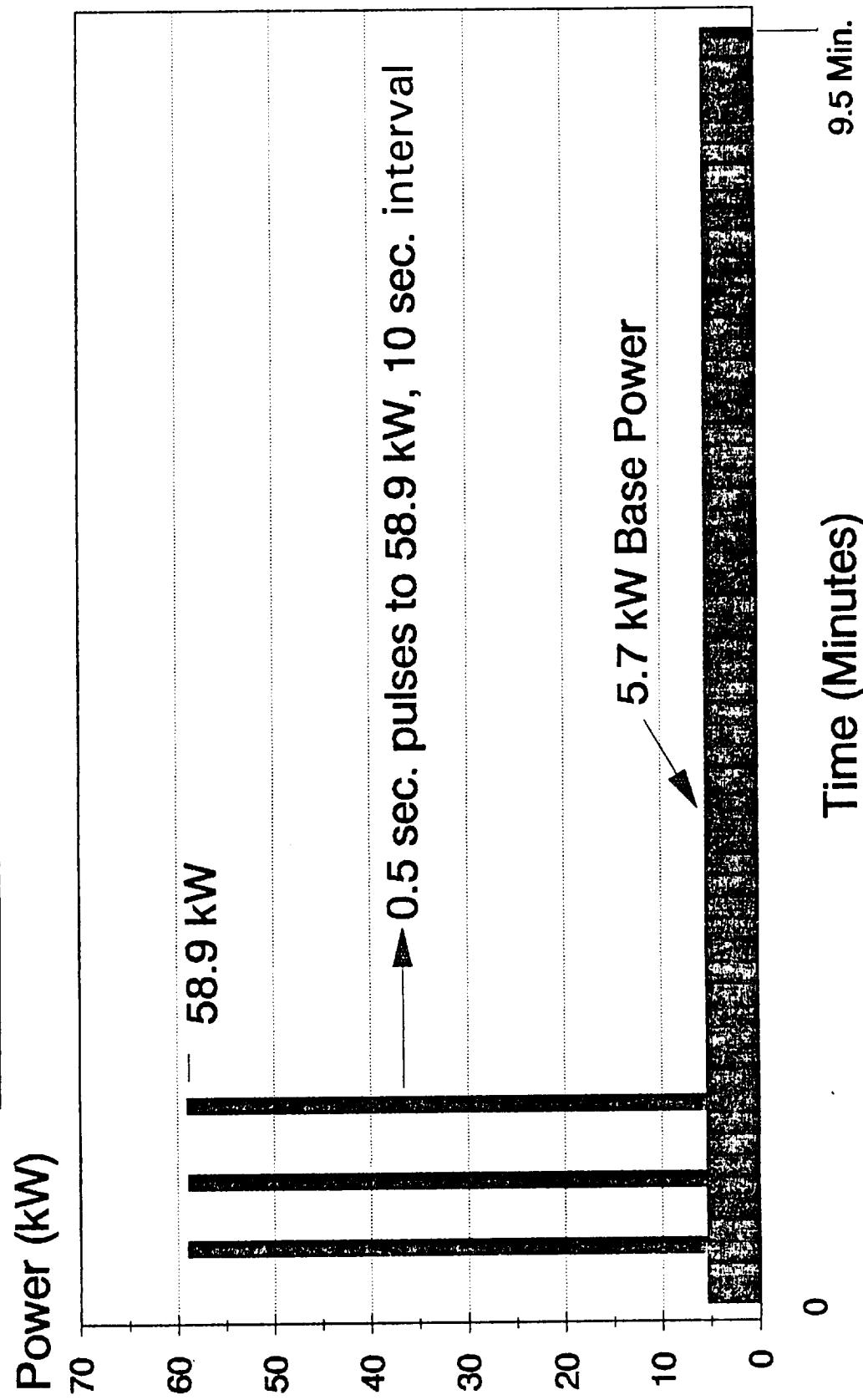
Battery Power Requirement (each SRB)



(1) Source is 10/15/91 presentation modified by
01/13/92 telecon with B.T.F. Lum and
C.L. Pond of Rockwell International Corporation

Figure 4

ALS Power Requirements



Source Voltage: 200-260 VDC

Source: General Dynamics Space Systems Division, Electromechanical Actuator ADP 2402, Avionics Area Review, Dec. 1990

Launch Vehicle Requirements at Battery Terminals

Figure 5

	SRB	ALS
Peak Power	(kW)	58.9
Base Power	(kW)	5.7
Pulse Duration	(sec)	0.5
Pulse Frequency	(sec)	10
Max. No. Pulses		54
Pulse Energy	(kWh)	0.40
Avg. Power(Base)	(kW)	5.70
Base Energy	(kWh)	0.90
Avg. Power(Total)	(kW)	8.20
Total Energy	(kWh)	1.30

Appendix A

Power Requirements -vs- Mission Phase for existing Shuttle APU/Hydraulic System

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Hydraulic Power vs Time -- Entry Case (design mission)	A-10
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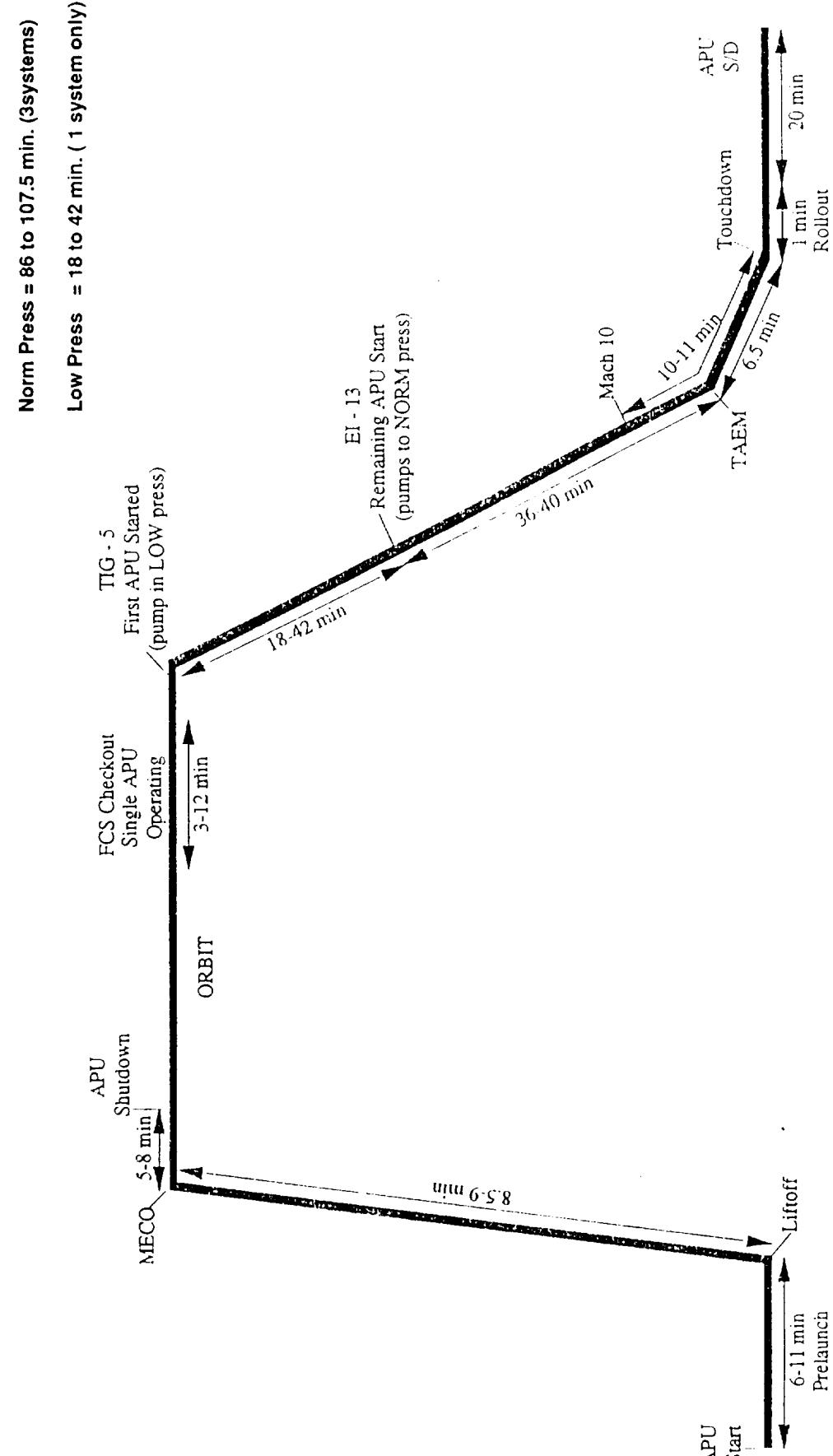
Power Requirements (each APU)*

- Normal Mission Profile
 - Ascent
 - FCS On-Orbit Checkout
 - Entry
- Abort Profile(AOA)
- Design Mission Profile
 - Ascent
 - FCS On-Orbit Checkout
 - Entry
 - AOA

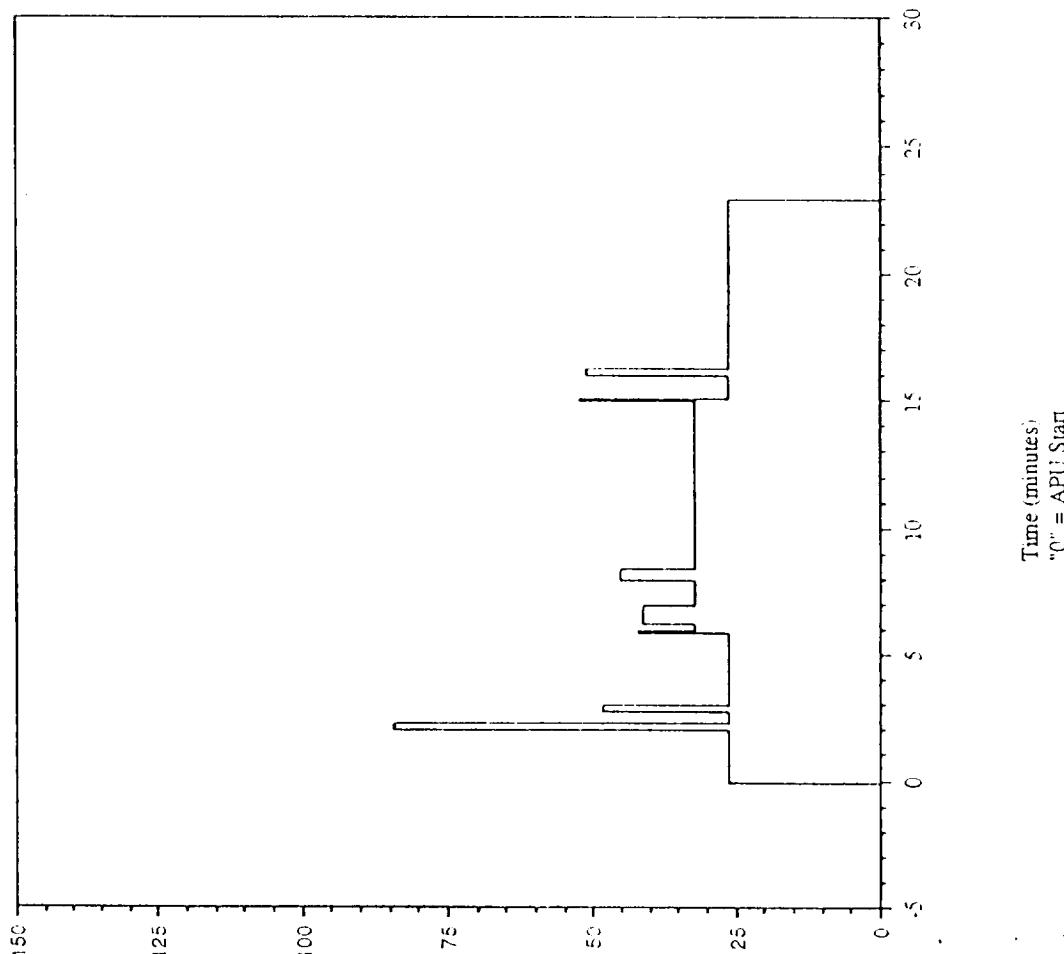
* APU shaft output (hydraulic pump input)

Normal Mission Profile

Appendix A



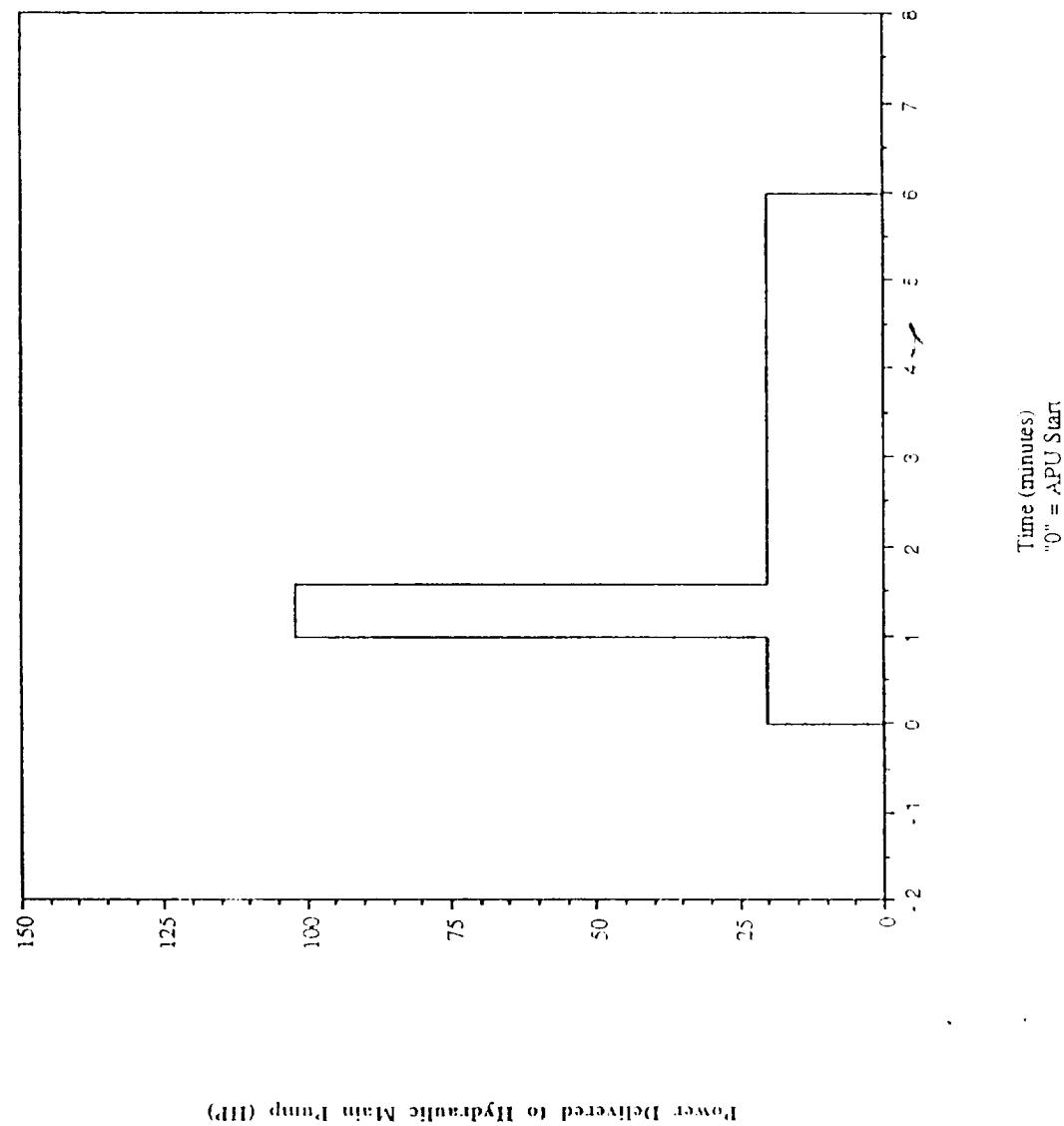
Hydraulic Power vs Time Ascent Case (nominal mission)



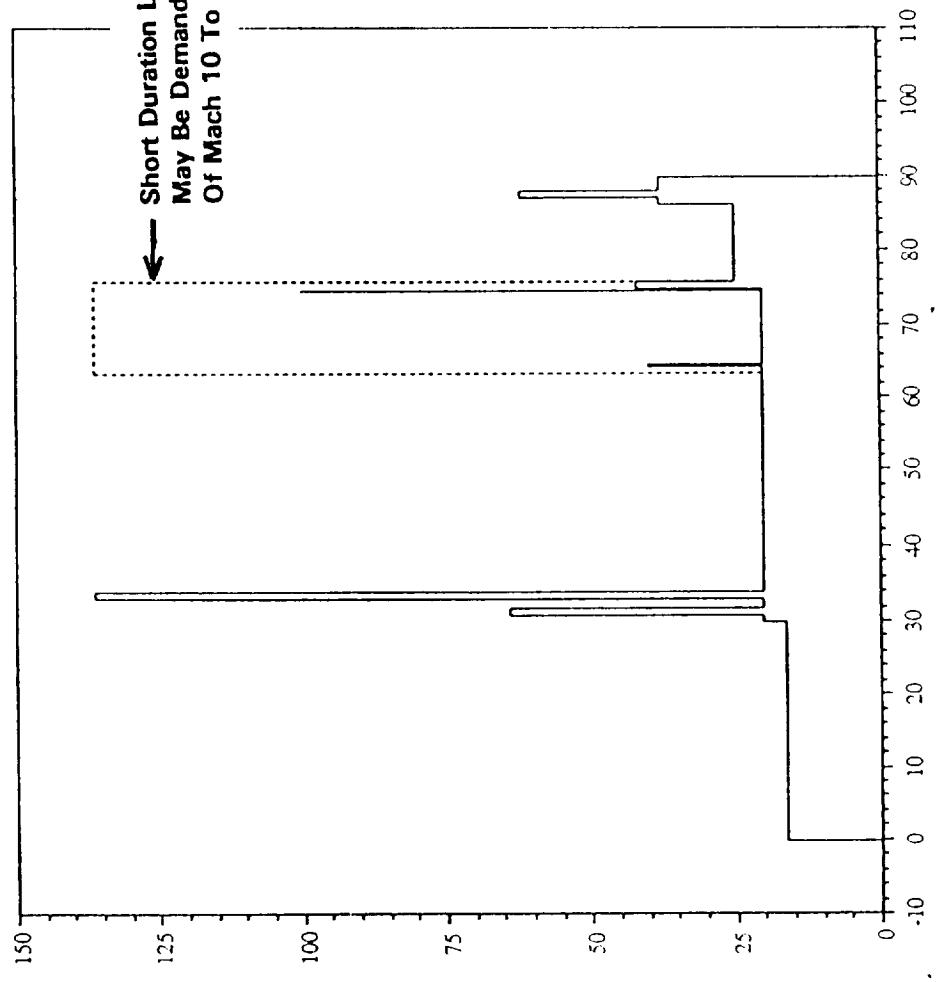
Power Delivered to Hydraulic Main Pump (HMP)

Time (minutes)
"0" = APU Start

Hydraulic Power vs Time FCS Checkout Case (nominal mission)



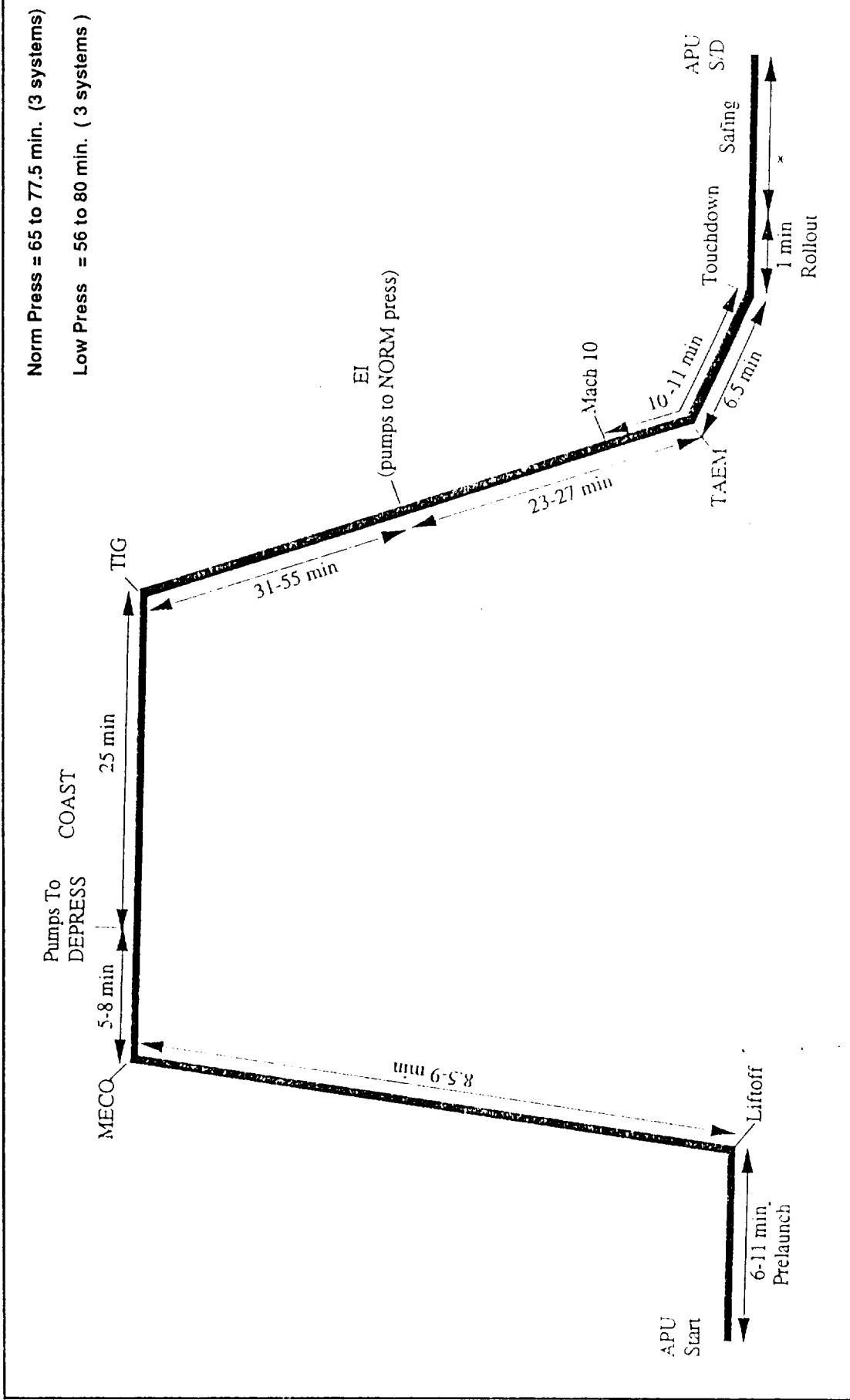
Hydraulic Power vs Time Entry Case (nominal mission)



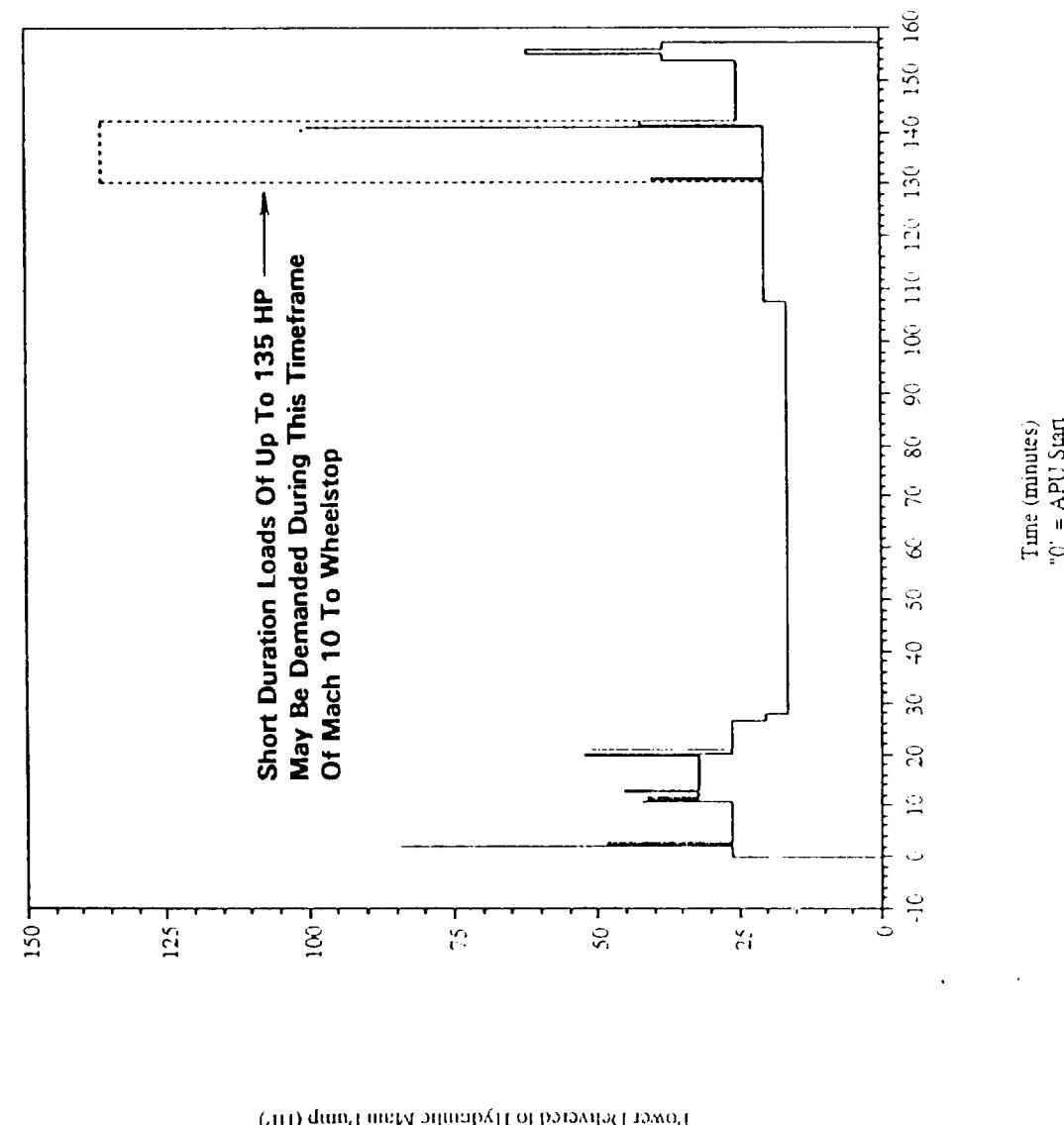
Power Delivered to Hydraulic Main Pump (HP)

Time (minutes)
"0" = APU Start

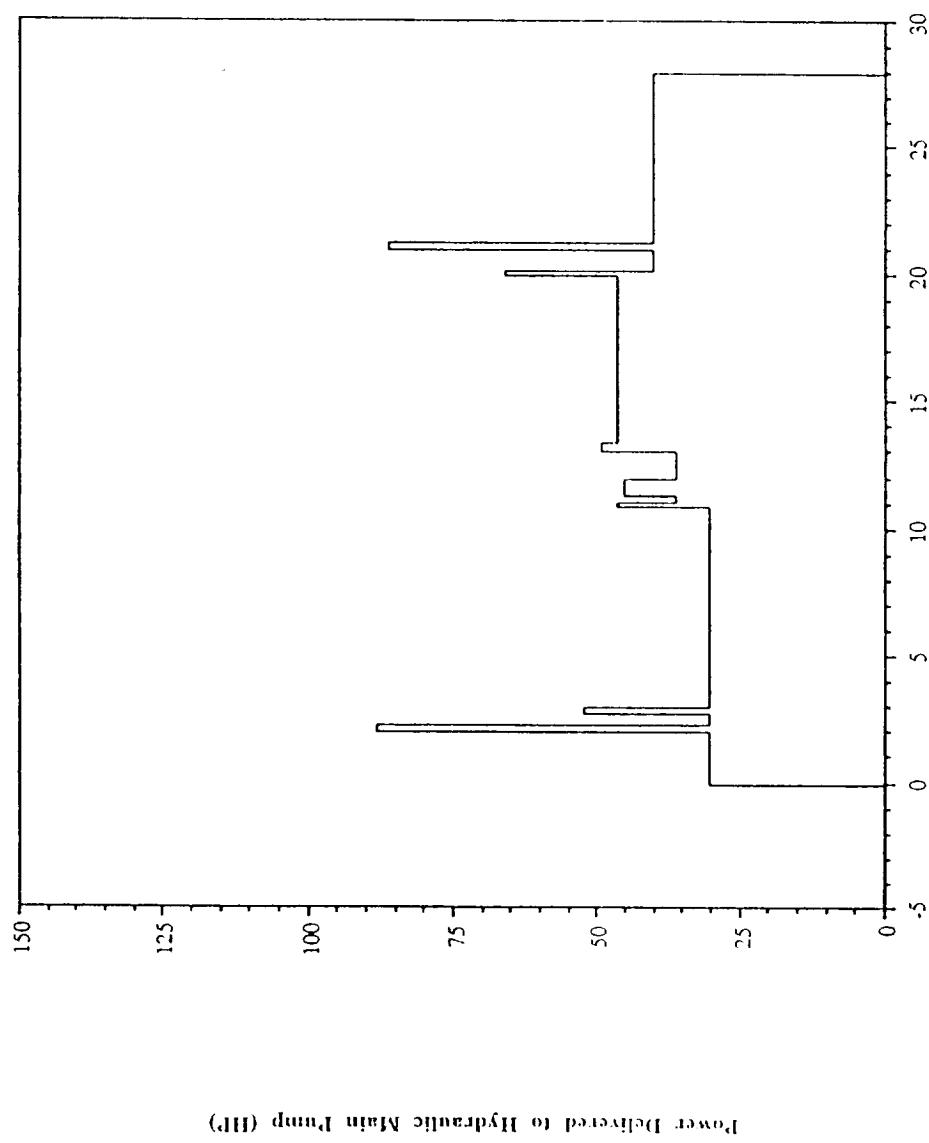
AOA Abort Profile



Hydraulic Power vs Time Abort-Once-Around Case (nominal abort mission)



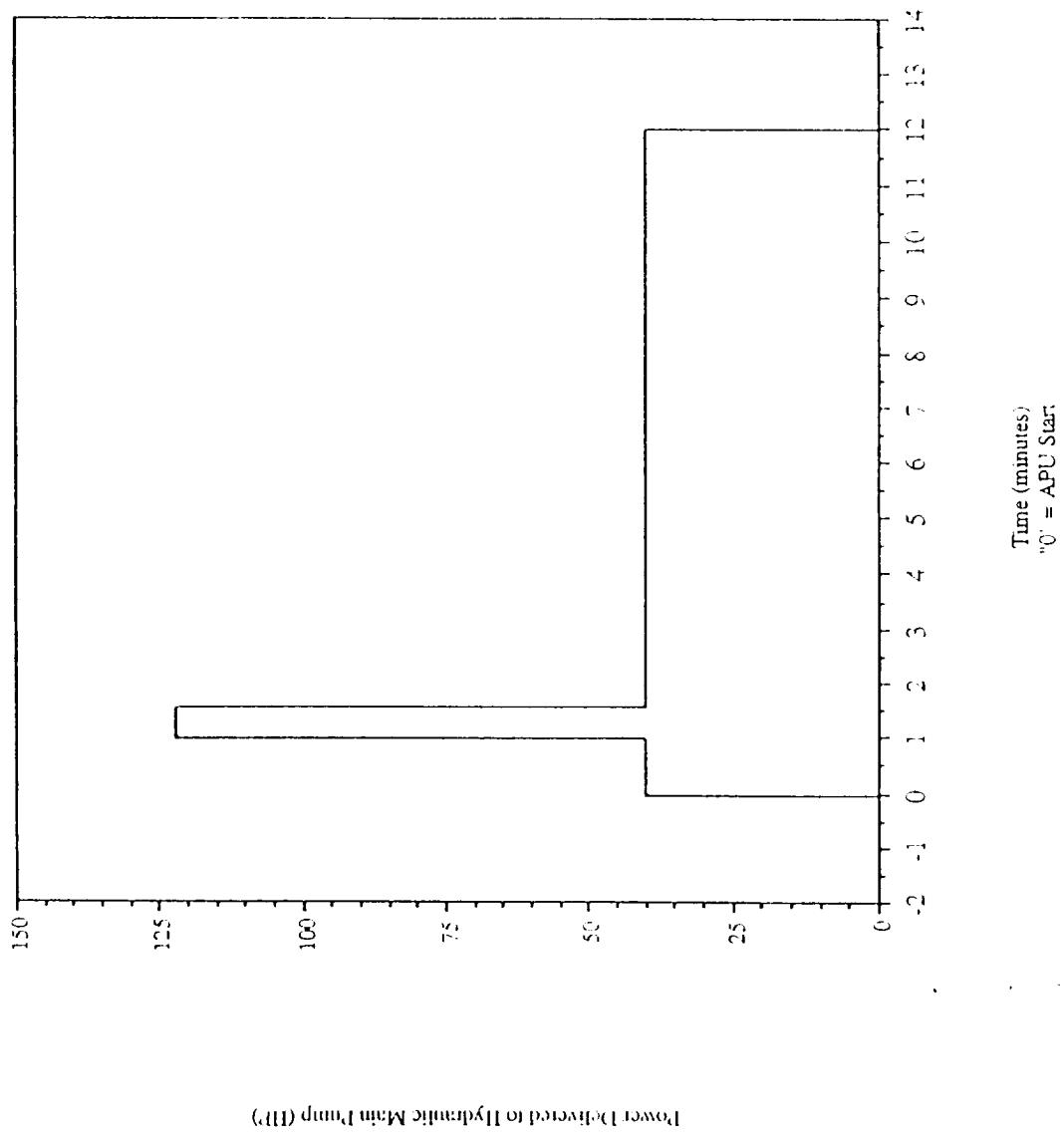
Hydraulic Power vs Time Ascent Case (design mission)



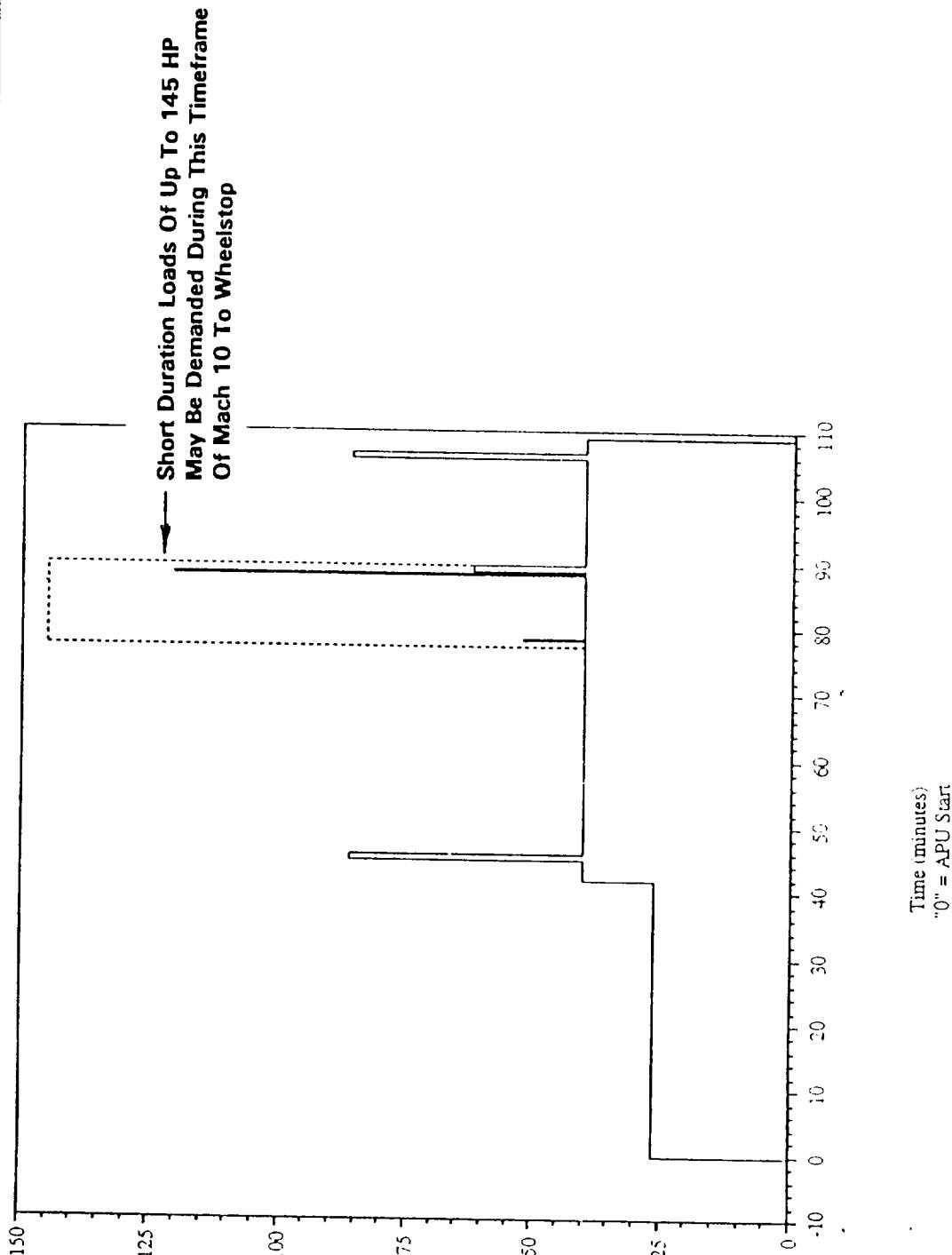
Time (minutes)
"0" = APC Start

Hydraulic Power vs Time FCS Checkout Case (design mission)

Appendix A



Hydraulic Power vs Time Entry Case (design mission)



Power Delivered to Hydraulic Main Pump

Time (minutes)
"0" = APU Start

Hydraulic Power vs Time Abort-Once-Around Case (design mission)

